# Naval Surface Warfare Center
## Carderock Division
West Bethesda, MD 20817-5700

**NSWCCD-TR-65–97/02** April 1997

Survivability, Structures, and Materials Directorate
Technical Report

# Variability in Geometry and Imperfections of Surface Ship Structural Scantlings

by

Paul E. Hess III and Bilal M. Ayyub

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## DEPARTMENT OF THE NAVY

NAVAL SURFACE WARFARE CENTER, CARDEROCK DIVISION
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1. Reference (a) directed the Naval Surface Warfare Center, Carderock Division (NSWCCD) to study the uncertainty associated with the geometry and imperfections of surface ship structural scantlings and statistically quantify this variability. Enclosure (1) documents this study. Recommended means, standard deviations, and probability density functions are presented for use in the development of a reliability-based design criteria for surface ship structures.

2. Comments or questions may be referred to the principal investigator, Mr. Paul E. Hess III, Code 654; telephone (301) 227-4118; e-mail, hess@oasys.dt.navy.mil.

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Enclosure (1)

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**13. ABSTRACT (Maximum 200 words)**

Random behavior of strength variables of a structure can cause the strength of the structure to vary beyond acceptable levels. The design strength is based on nominal values for variables such as yield stress of the material, plate thickness, modulus of elasticity, and so forth. The actual values of these variables are often different from the nominal, or design values. Understanding the randomness of the basic strength variable behavior allows the designer to account for this in the design strength of the structure. The basic structural strength variables may be classified into material variables, such as yield strength and ultimate strength, and geometry or construction variables, such as plate thickness and stiffener height. The objective of this study is to quantify the randomness or uncertainty found in the geometric variables used in the analysis and design of surface ship structures. The bulk of the data used in this study are for U.S. Navy ships. Additional data is provided for U.S. Coast Guard and commercial vessels. The results of this study can be used in the development of reliability-based design criteria, tolerance limits, and the assessment of uncertainty in strength predictions.

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# CONTENTS

# 1.0 INTRODUCTION

## 1.1 Background

Random behavior of the basic strength variables of a structure can cause its strength to vary beyond acceptable levels (Thoft-Christensen and Baker, 1982). The strength of a structure for design purposes is calculated using nominal, or design values for variables such as yield stress of the material, plate thickness, modulus of elasticity, etc. The actual values of these variables as used in the resulting structure, are often different from the nominal values. These actual values tend to behave in a somewhat random manner, causing random behavior of the actual structural strength. Understanding the randomness of the basic strength variables allows the designer to account for this variability in the design phase and make allowances for it.

The basic structural strength variables may be grouped into two classes, material variables (such as yield strength and ultimate strength) and geometry variables (such as plate thickness and stiffener height). The geometric variables may also be called construction variables.

## 1.2 Objective and Scope

The objective of this study is to present estimates of the statistical characteristics of geometric, basic strength variables as reported in the literature, measurements taken on-board ships, and raw material measurements (before use in ship fabrication). The use of the basic strength variable statistical estimates may be used for calibration efforts of the reliability design and analysis tools, with the caveat that they may not necessarily be stationary random processes, nor completely representative of the geometric uncertainty as found in all surface ship structures.

Statistical estimates of the uncertainty for the following basic strength variables are presented: plate thickness, stiffener length and spacing, stiffener web height, web thickness, flange breadth, and flange thickness, stiffener strong and weak axis distortion, and

unstiffened plate distortion. The effects of the following factors on the plate thickness uncertainty are investigated: nominal thickness, steel type, data source, ordering specification, measurement technique, presence of a surface coating, and amount of plate deformation.

## 1.3 Methodology

Data on geometric variables were collected from a variety of sources which can be classified in numerous ways. Sample sets have been created from measurements taken of materials prior to fabrication as well as from finished structures. These samples encompass both materials used in actual ship construction and in scaled down models of ship components. The histories of these sample sets are maintained to preserve the data. The statistical analyses were conducted with rather general groupings of these sets.

A means of addressing the uncertainty inherent in geometric variables is to study the bias between the actual (measured) value and the values used for design, and to create a statistical (probabilistic) model of this bias for use in reliability analysis and design methods.

### 1.3.1 Bias

The uncertainty in basic strength variables can be quantified using two types of bias: the *ratio* bias and the *difference* bias. The *ratio* bias is the ratio between the measured value and the nominal (or design) value for strength variables as follows:

$$b_R = \frac{measured\ value}{nominal\ value}.$$

The *difference* bias is the difference, or error, between the measured value and the nominal value:

$$b_D = measured\ value - nominal\ value.$$

For geometric variables such as thickness, breadth and height, variations from nominally specified values may not be dependent upon nominal values. For small nominal values of

these variables, the ratio bias may overestimate the variability, while for larger variable values, it may underestimate the variability. Therefore the error, or difference, between the measured and nominal values can be analyzed along with the ratio of these values.

Uncertainty in distortion, or eccentricity, can be described using a normalized value which is the ratio of the distortion to a dimension of the distorted structural component. An example in this case is the normalization of stiffener distortion by the stiffener length.

### 1.3.2 Probability Density Functions

The probability density function (p.d.f.) is a curve for which probability density, the y-axis value, is plotted against possible values of a specific random variable. Integration of the area under this curve, between two bounds, gives a measure of the probability that a value will occur between the chosen bounds. The legitimacy of a p.d.f. depends upon two properties:

1. Values of the p.d.f. are always greater than zero or $f_X(x) \geq 0$.

2. The area of the p.d.f. is always equal to one or $\int_{-\infty}^{+\infty} f_X(x)dx = 1$.

Additional information about the p.d.f., and probability theory in general, is available in Ang and Tang (1975), Ayyub and McCuen (1997) and Thoft-Christensen and Baker (1982).

The computer program BestFit (Version 2.0c) was used to explore which probability density functions (p.d.f.) are most representative of the sample data. BestFit uses the LevenBerg-Marquardt Method (BestFit User's Guide, 1995) to fit p.d.f.'s from a library of 21 continuous functions to the sample data. Appendix A describes the p.d.f.'s used in the analysis. The ranking of the p.d.f.'s was done using Chi-squared, Kolmagorov-Smirnov and Anderson-Darling goodness-of-fit tests. Brief descriptions of these tests are provided in Appendix B.

The top three p.d.f.'s are presented for each variable as ranked using each of the three goodness-of-fit tests. The calculated goodness-of-fit statistics show that very few of the cases

satisfy any realistic level of significance ($\alpha$), usually violating the associated critical value and limiting the relevance of the tests. Therefore, the recommended p.d.f.'s are based on a subjectively weighted averaging of the numerical goodness-of-fit ranks.

The use of BestFit requires an input of a bin (class or grouping) size for the histogram generation. The equations $1+3.3\text{Log}_{10}N$ (Ayyub and McCuen, 1997) and $(4N)^{2/5}$ (suggested in BestFit) were used to gain an initial estimate of appropriate bin sizes. These numbers were varied and a selection was made that caused the histogram to approach a relatively smooth curve which seemed to best represent the data.

# 2.0 DATA SOURCES

## 2.1 Measurements Taken from Plates Before Construction

### 2.1.1 NSWC Model Tests

The Naval Surface Warfare Center, Carderock Division (NSWCCD) has performed various scale model tests to investigate failure mechanisms and strength behavior. The thicknesses of the uncoated plating used in these tests were measured with a micrometer.

### 2.1.2 Newport News Shipbuilding

Newport News Shipbuilding measured plating thickness variability, as part of a quality assurance program, using ultrasonic techniques (UT) and micrometer measurements. The plates were assumed to be without any surface coating. For this study, each measurement was considered to be a data point unto its own, even though numerous data points were taken from the same plate. This was considered appropriate based on the variability found in the measured thickness of each plate.

### 2.1.3 Coast Guard

Plate thickness measurements were taken of material destined for use in Coast Guard vessels. The specified (nominal) thicknesses used in ordering this material were less than the equivalent Navy nominal thickness. An example of this would be the use of 10.0# (0.2451 inch thickness) plating by the Coast Guard, as opposed to 10.2# (0.25 inch thickness) as used by the Navy. The Coast Guard specified nominal value is used in the calculation of the bias, matching the data trends found in other sample sets.

## 2.2 Measurements Taken from Plates and Sections After Construction

### 2.2.1 NSWC Shipboard Measurements

For this study, measurements were taken on board active ships in readily accessible areas. Panel access was restricted due to equipment and insulation and resulted in longitudinal and transverse bulkheads being the most frequently measured panels. All

measured areas were coated with paint of unknown thickness. The nominal values of the scantlings were found from available ship structural drawings. Appendix C is a write-up by the personnel who conducted the ship survey describing the methods by which measurements were made.

Stiffener height (HSW), web thickness (TSW), flange breadth (BSF), and flange thickness (TSF) were measured at three locations on each stiffener, when no interferences were present. Each of these measurements is considered a data point in the analysis even though it comes from the same member.

Distortion measurements of the stiffeners and plating were obtained during this survey. The plating distortion was measured to obtain a maximum deflection. The weak and strong axis stiffener distortions were also recorded. The weak-axis distortion reflects the stiffeners predisposition to experience tripping failure. The strong-axis distortion is more indicative of stiffened panel collapse, and is sometimes called *lateral* distortion.

### 2.2.2 SSC-364

The Ship Structure Committee published a report (Jennings et al 1991) on the maximum inelastic plate distortions found in a ship hull. Plate thickness data was gathered around the deformed region using a UT measuring device. The measurements were taken primarily on the shell, with unknown amounts of paint coating the material. The reported distortion data is not used in this study, as it is the result of extreme environmental loads or impacts, and as such should be considered damaged.

### 2.2.3 NSWCCD Bending Model

Unstiffened plating distortion measurements were taken from a large scale model of a prismatic ship midsection prior to testing at NSWCCD. These panels were components of an advanced double hull design, and so not bounded by stiffeners, but by plating of similar thickness. The mode shapes were recorded, but only the maximum deflection values from these measurements are used in this study.

# 3.0 PLATE THICKNESS

## 3.1 Introduction

Plate thickness is considered a rather important variable in ship structural design. Variations in the thickness can play an important role in the uncertainty of the strength of the final product as shown in Hess et al (1994). There is also the potential for significant variation in the weight and cost of the structure. The uncertainty in the plate thickness may be described using a variety of classifications. The total population, as well as assorted subsets, are discussed below to explore factors influencing the uncertainty.

## 3.2 Plate Thickness Uncertainty Literature Survey

Statistical information on plate thickness $t$ of naval shipbuilding steel was summarized by Daidola and Basar (1980) as given in Tables 3.2a and 3.2b. These tables provide tolerances and statistical information on variation of plate thickness used in shipbuilding. According to Minnick and St. John (1987), probably the only detailed source of information for plate thickness is that of Basar and Stanley (1978). Mansour and Faulkner (1973) reported that the coefficient of variation of plate thickness is greatest for thin plates. Calculation of the standard deviation for a plate thickness $t$ based on its tolerance can be performed by dividing the tolerance by 3 (Daidola and Basar 1980). This is true if the underlying probability distribution of $t$ is normal and 99.7 percent of the measurements generally fall within the tolerance limit. The mean value of $t$ can be chosen from its reporting context, and hence the coefficient of variation (c.o.v.) can be computed by dividing the standard deviation by $t$. The calculated values for the standard deviations and c.o.v.'s of $t$ are shown in Tables 3.2a and 3.2b. Table 3.2c summarizes the calculated averages and ranges for the standard deviation and the coefficient of variation of $t$. The calculated averages in Table 3.2c were based on the data shown in Tables 3.2a and 3.2b.

**Table 3.2a**. Uncertainty in Plate Thickness $t$ based on Tolerance (Receipt inspection)

| Data Point | Tolerance (in) | Standard Deviation of $t$ (in) | Mean of $t$ (in) | c.o.v. of $t$ |
|---|---|---|---|---|
| 1 | 1/8 | 0.0417 | $t$ | $0.0417/t$ |
| 2 | 1/32 | 0.0104 | $t$ | $0.0104/t$ |
| 3 | 1/64 | 0.0052 | $t$ | $0.0052/t$ |
| 4 | 1/8 | 0.0417 | $t$ | $0.0417/t$ |

$t$ = plate thickness in inches

**Table 3.2b**. Uncertainty in Plate Thickness Based on Tolerance (Undercut)

| Data Point | Tolerance (in) | Standard Deviation of $t$ (in) | Mean of $t$ (in) | c.o.v. of $t$ |
|---|---|---|---|---|
| 1 | 1/32 | 0.0104 | $t$ | $0.0104/t$ |
| 2 | 1/16 | 0.0208 | $t$ | $0.0208/t$ |
| 3 | 1/32 | 0.0104 | $t$ | $0.0104/t$ |
| 4 | 1/32 | 0.0104 | $t$ | $0.0104/t$ |
| 5 | 1/32 | 0.0104 | $t$ | $0.0104/t$ |
| 6 | 1/32 | 0.0104 | $t$ | $0.0104/t$ |
| 7 | 1/16 | 0.0208 | $t$ | $0.0208/t$ |
| 8 | 1/32 | 0.0104 | $t$ | $0.0104/t$ |
| 9 | 1/16 | 0.0208 | $t$ | $0.0208/t$ |

$t$ = plate thickness in inches, Undercut = further cutting of plate by the recipient after delivery

**Table 3.2c**. Averages and Ranges of Standard Deviation and c.o.v. for Plate Thickness $t$

| | Standard Deviation of $t$ (in) | c.o.v. of $t$ |
|---|---|---|
| Average | 0.0172 | $0.0172/t$ |
| Minimum | 0.0052 | $0.0052/t$ |
| Maximum | 0.0417 | $0.0417/t$ |

## 3.3 Plate Thickness Data

The makeup of the plate thickness data is discussed in the following sections. For this study, the overall uncertainty of the plate thickness is investigated. Schemes of classification are carried out based upon the available information. The resulting subsets of data were investigated to assess the influence that these factors might have on the uncertainty. The statistics of the union of all sets of plate thickness measurements are presented in Table 3.3. The fitting of a p.d.f. will be discussed in Section 3.5.

**Table 3.3.** Plate Thickness Statistical Analysis.

|  | Ratio Bias | Difference Bias (in.) |
|---|---|---|
| Mean | 1.04849 | 0.014732 |
| Standard Deviation | 0.04592 | 0.020997 |
| c.o.v. (%) | 4.38 | n/a |
| Standard Error | 0.000968 | 0.000442 |
| Median | 1.043698 | 0.0061 |
| Mode | 1.043233 | 0.0046 |
| Sample Variance | 0.002109 | 0.000441 |
| Kurtosis | 5.804 | 4.201 |
| Skewness | 1.524 | 1.979 |
| Range | 0.4692 | 0.1643 |
| Minimum | 0.9068 | -0.0233 |
| Maximum | 1.376 | 0.141 |
| Count | 2252 | 2252 |
| Confidence Level (95.0%) | 0.001898 | 0.000868 |

## 3.4  Factors Which Influence Plate Thickness Bias

The effects of the following factors on the plate thickness uncertainty are investigated: nominal thickness, steel type, data source, ordering specification, measurement technique, presence of a surface coating, and amount of plate deformation. The correlation coefficients of these factors were calculated and are shown in Table 3.4.

**Table 3.4.** Correlation Coefficients of Factors Which Influence Plate Thickness.

|  | Nominal Thickness | Steel Type | Source | Ordering Spec. | Meas. Technique | Coating? | Plate Shape |
|---|---|---|---|---|---|---|---|
| Nom. Thickness | 1 |  |  |  |  |  |  |
| Steel Type | 0.163 | 1 |  |  |  |  |  |
| Source | 0.746 | 0.233 | 1 |  |  |  |  |
| Ordering Spec. | 0.690 | 0.294 | 0.902 | 1 |  |  |  |
| Meas. Technique | 0.655 | 0.566 | 0.846 | 0.748 | 1 |  |  |
| Coating? | 0.146 | 0.477 | 0.649 | 0.606 | 0.844 | 1 |  |
| Plate Shape | -0.437 | -0.045 | -0.795 | -0.626 | -0.775 | -0.791 | 1 |

The interdependencies between the variables are quite high with correlation coefficients approaching unity for multiple factors. The following analyses investigate each factor independently and should be viewed with consideration of the lack of independence shown above.

### 3.4.1  Effect of Nominal Thickness on Plate Thickness Bias

The nominal thickness is the value used in ordering the plate and for design and analysis. The plate thickness ratio bias and difference bias do not appear to be influenced by the nominal thickness of the plating as seen in Tables 3.4.1a and 3.4.1b and Figures 3.4.1a and 3.4.1b. This lack of a noticeable trend may be due to the influence of the source of the data, the ordering specification and the measurement technique.

**Table 3.4.1a.** Plate Thickness Ratio Bias Classed by Nominal Value.

| Nominal Value | Mean Ratio Bias | Standard Deviation | c.o.v. (%) | Number of Samples |
|---|---|---|---|---|
| 0.0819 | 1.052296 | 0.0164648 | 1.5647 | 224 |
| 0.1064 | 1.051047 | 0.0168023 | 1.5986 | 522 |
| 0.125 | 0.976150 | 0.0177093 | 1.8142 | 32 |
| 0.1309 | 1.033802 | 0.0177583 | 1.7178 | 268 |
| 0.1554 | 1.024085 | 0.0144680 | 1.4128 | 14 |
| 0.1677 | 1.054711 | 0.0116144 | 1.1012 | 64 |
| 0.2188 | 1.154276 | 0.0330454 | 2.8629 | 9 |
| 0.2289 | 1.007402 | 0.0288391 | 2.8627 | 106 |
| 0.25 | 1.012998 | 0.0433690 | 4.2813 | 87 |
| 0.2813 | 1.076926 | 0.0407649 | 3.7853 | 33 |
| 0.3125 | 1.010909 | 0.0446397 | 4.4158 | 145 |
| 0.34375 | 1.072485 | 0.0478602 | 4.4626 | 33 |
| 0.375 | 1.152199 | 0.0583823 | 5.0670 | 161 |
| 0.4375 | 1.054759 | 0.0492431 | 4.6687 | 35 |
| 0.4738 | 1.026074 | 0.0042637 | 0.4155 | 39 |
| 0.5 | 0.997600 | 0.0223428 | 2.2397 | 20 |
| 0.5625 | 1.044231 | 0.0285345 | 2.7326 | 79 |
| 0.625 | 1.036328 | 0.0150938 | 1.4565 | 251 |
| 0.6875 | 1.024595 | 0.0250678 | 2.4466 | 22 |
| 0.75 | 1.095078 | 0.0211289 | 1.9294 | 81 |
| 0.875 | 1.023619 | 0.0311311 | 3.0413 | 27 |

**Table 3.4.1b.** Plate Thickness Difference Bias Classed by Nominal Value.

| Nominal Value | Mean Difference Bias (in.) | Standard Deviation (in.) | c.o.v. (%) | Number of Samples |
|---|---|---|---|---|
| 0.0819 | 0.004283036 | 0.00134847 | 31.48393 | 224 |
| 0.1064 | 0.005431418 | 0.00178776 | 32.9152 | 522 |
| 0.125 | -0.00298125 | 0.00221366 | -74.2527 | 32 |
| 0.1309 | 0.004424627 | 0.00232456 | 52.53689 | 268 |
| 0.1554 | 0.003742857 | 0.00224832 | 60.06963 | 14 |
| 0.1677 | 0.009175 | 0.00194773 | 21.22866 | 64 |
| 0.2188 | 0.033755556 | 0.00723034 | 21.4197 | 9 |
| 0.2289 | 0.00169434 | 0.00660127 | 389.6071 | 106 |
| 0.25 | 0.003249425 | 0.01084226 | 333.667 | 87 |
| 0.2813 | 0.021639394 | 0.01146718 | 52.99215 | 33 |
| 0.3125 | 0.003408966 | 0.01394991 | 409.2126 | 145 |
| 0.34375 | 0.024916667 | 0.01645195 | 66.02789 | 33 |
| 0.375 | 0.057074534 | 0.02189336 | 38.35925 | 161 |
| 0.4375 | 0.023957143 | 0.02154386 | 89.92666 | 35 |
| 0.4738 | 0.012353846 | 0.00202014 | 16.35233 | 39 |
| 0.5 | -0.0012 | 0.01117139 | -930.949 | 20 |
| 0.5625 | 0.024879747 | 0.01605064 | 64.51289 | 79 |
| 0.625 | 0.022705179 | 0.0094336 | 41.54821 | 251 |
| 0.6875 | 0.016909091 | 0.01723413 | 101.9223 | 22 |
| 0.75 | 0.071308642 | 0.01584664 | 22.22261 | 81 |
| 0.875 | 0.020666667 | 0.02723968 | 131.8049 | 27 |
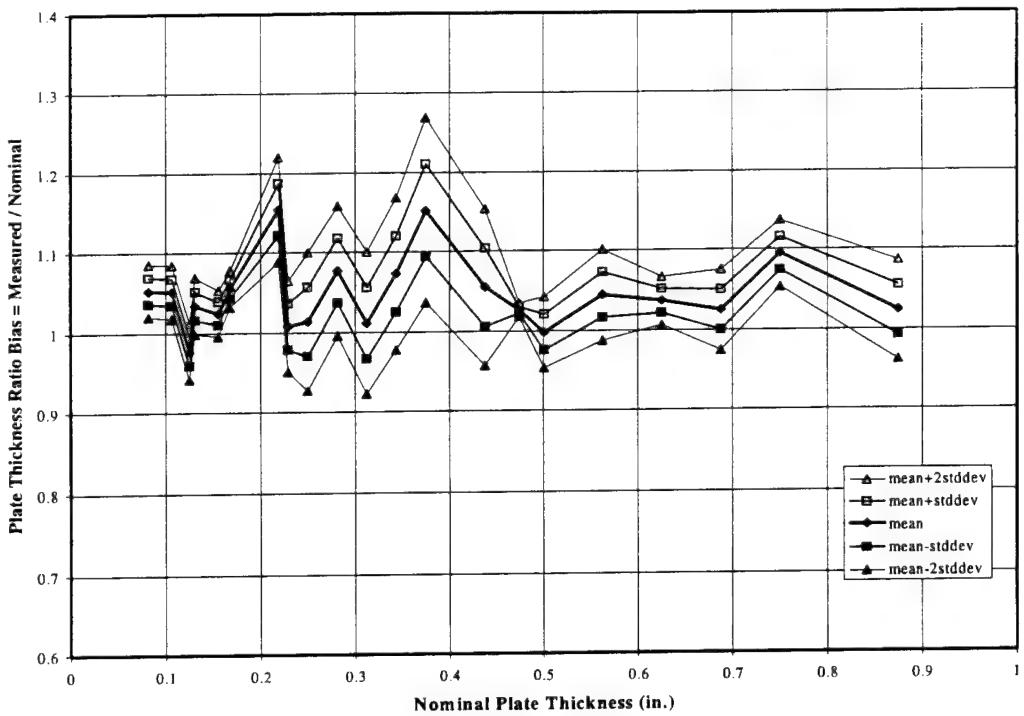
**FIGURE 3.4.1a.** The Plate Thickness Ratio Bias Versus the Nominal Thickness.
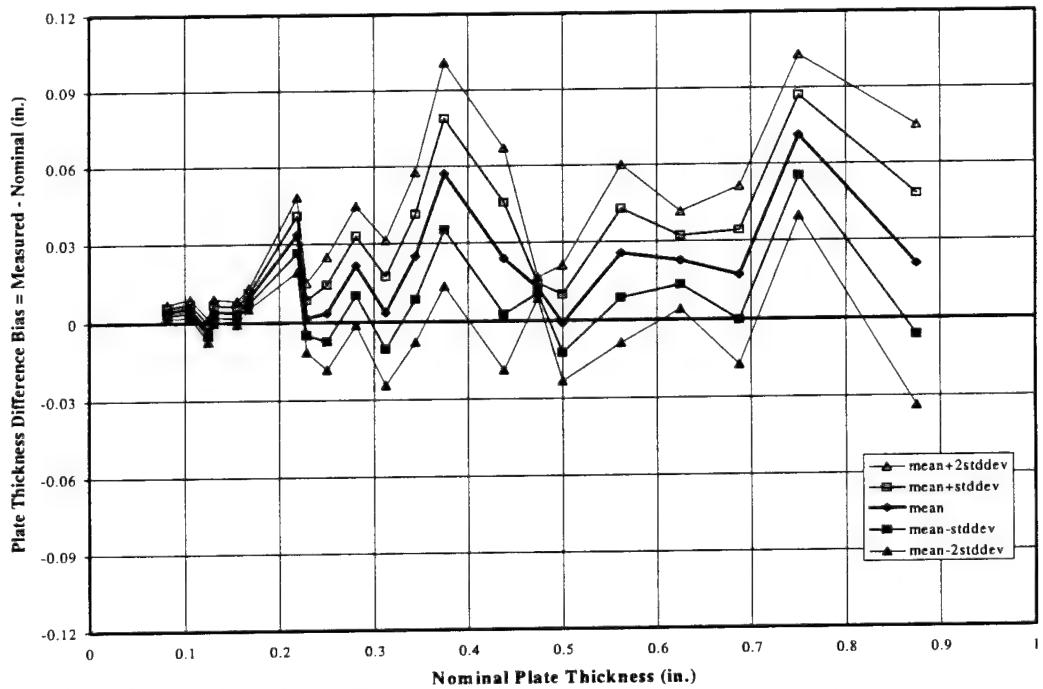


**FIGURE 3.4.1b.** The Plate Thickness Difference Bias Versus the Nominal Thickness.

## 3.4.2 *Effect of Material Type on Plate Thickness Bias*

From the statistics shown in Tables 3.4.2a and 3.4.2b, it may be inferred that, as the yield strength of the plating increases, so do the ratio and difference biases. The uncertainty associated with the ratio bias decreases with the nominal yield strength of the material, while for the difference bias, the uncertainty increases with the nominal yield strength.

**Table 3.4.2a.** Plate Thickness Ratio Bias Classed by Material type.

| Material | Mean Ratio Bias | Standard Deviation | c.o.v. (%) | Number of Samples |
|---|---|---|---|---|
| OS | 1.0346 | 0.062341 | 6.026 | 471 |
| HTS | 1.0523 | 0.058489 | 5.558 | 272 |
| HY-80 | 1.1180 | 0.046326 | 4.144 | 147 |

**Table 3.4.2b.** Plate Thickness Difference Bias Classed by Material Type.

| Material | Mean Difference Bias (in.) | Standard Deviation (in.) | c.o.v. (%) | Number of Samples |
|---|---|---|---|---|
| OS | 0.015733 | 0.022893 | 146 | 471 |
| HTS | 0.024453 | 0.022343 | 91.4 | 272 |
| HY-80 | 0.059154 | 0.024852 | 42.0 | 147 |
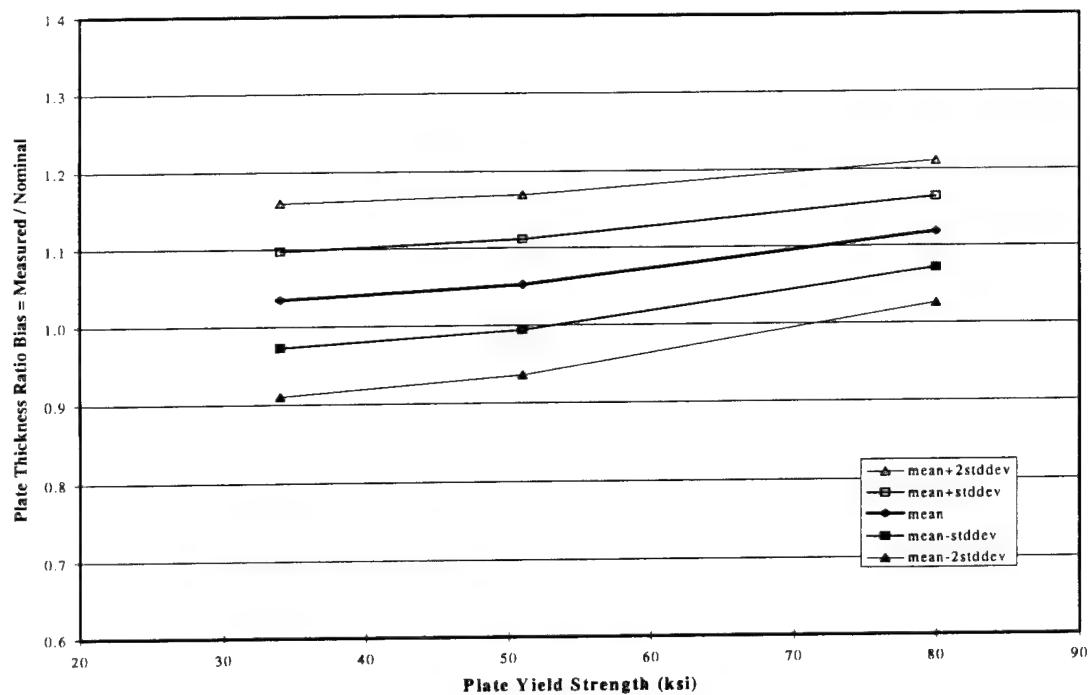
**FIGURE 3.4.2a.** The Plate Thickness Ratio Bias Versus the Nominal Yield Strength.
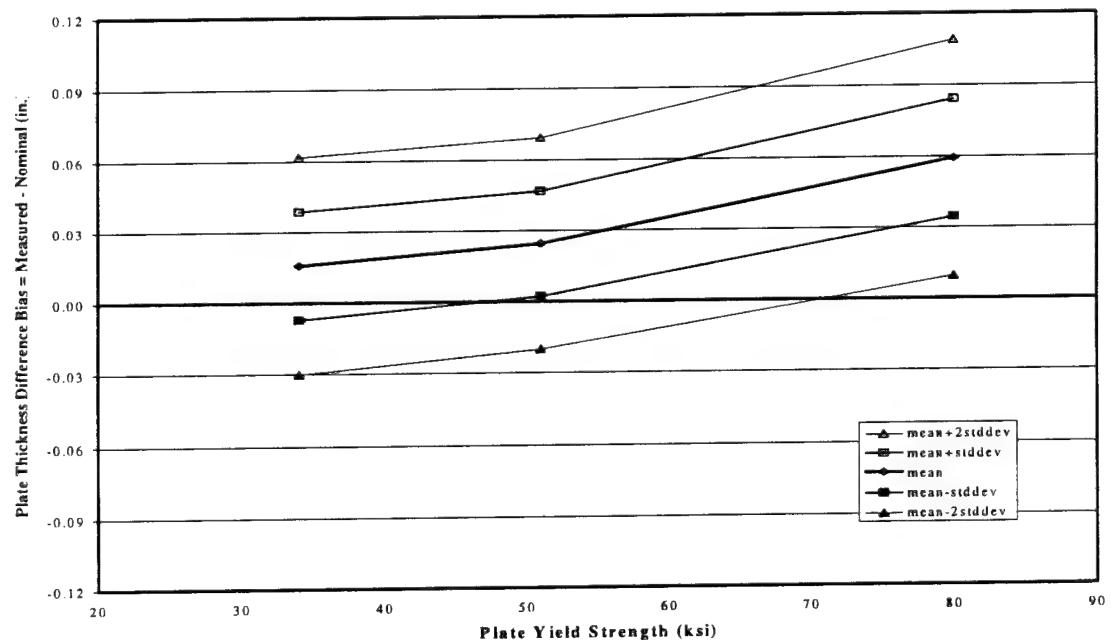


**FIGURE 3.4.2b.** The Plate Thickness Difference Bias Versus the Nominal Yield Strength.

*3.4.3 Effect of the Data Source on Plate Thickness Bias*

The source of the data had a large impact on the results with greater uncertainty associated with the NSWC test and on-ship data and the data reported in SSC-364. The Newport News data and the Coast Guard data appears have less associated variability. The Coast Guard data set primarily consists of plate thicknesses less than 0.25 inches. This helps explain the closeness of the difference bias relative to the greater uncertainty in the ratio bias. The Newport News thickness samples were nominally 0.625 inches, resulting in the difference bias showing a greater variability than the ratio bias. The breakdown of the number of samples of different thicknesses for each source are shown in Table 3.3.3c.

The higher bias of the on-ship measured thicknesses (NSWC and SSC-364) may result from the conditions under which the measurements were made. These conditions include the presence of paint on the surface through which ultrasonic measurements were taken. The measurements of materials taken before construction (Newport News, NSWC tests and Coast Guard data) were made with either a micrometer or ultrasonic measuring device without the impact of layers of surface treatments.

**Table 3.4.3a.** Plate Thickness Ratio Bias Classed by the Data Source.

| Data Source | Mean Ratio Bias | Standard Deviation | c.o.v. (%) | Number of Samples |
|---|---|---|---|---|
| Coast Guard | 1.04289 | 0.02251 | 2.158 | 1237 |
| Newport News | 1.03734 | 0.01409 | 1.358 | 239 |
| NSWC (tests) | 1.00263 | 0.04122 | 4.111 | 239 |
| NSWC (on ship) | 1.10456 | 0.03563 | 3.226 | 118 |
| SSC-364 | 1.08173 | 0.07115 | 6.577 | 419 |

**Table 3.4.3b.** Plate Thickness Difference Bias Classed by the Data Source.

| Data Source | Mean Difference Bias (in.) | Standard Deviation (in.) | c.o.v. (%) | Number of Samples |
|---|---|---|---|---|
| Coast Guard | 0.005078 | 0.003274 | 64.5 | 1237 |
| Newport News | 0.023335 | 0.008806 | 37.7 | 239 |
| NSWC (tests) | 0.001126 | 0.011385 | 1011 | 239 |
| NSWC (on ship) | 0.057414 | 0.026679 | 46.5 | 118 |
| SSC-364 | 0.034069 | 0.026688 | 78.3 | 419 |

**Table 3.4.3c.** Plate Thickness Data Source and Sample Nominal Thickness Distribution.

| Thickness Range | NSWC (Tests) | Coast Guard | NSWC (On Ship) | Newport News | SSC-364 |
|---|---|---|---|---|---|
| 0.0 - 0.125 | 32 | 746 | | | |
| 0.125 - 0.25 | 87 | 452 | 9 | | |
| 0.25 - 0.375 | 120 | | 42 | | 210 |
| 0.375 - 0.50 | | 39 | | | 55 |
| 0.50 - 0.625 | | | | 239 | 91 |
| 0.625 - 0.75 | | | 67 | | 36 |
| 0.75 - 0.875 | | | | | 27 |

Note: membership inside a range is based on being greater than the lower limit and less than or equal to the upper limit.
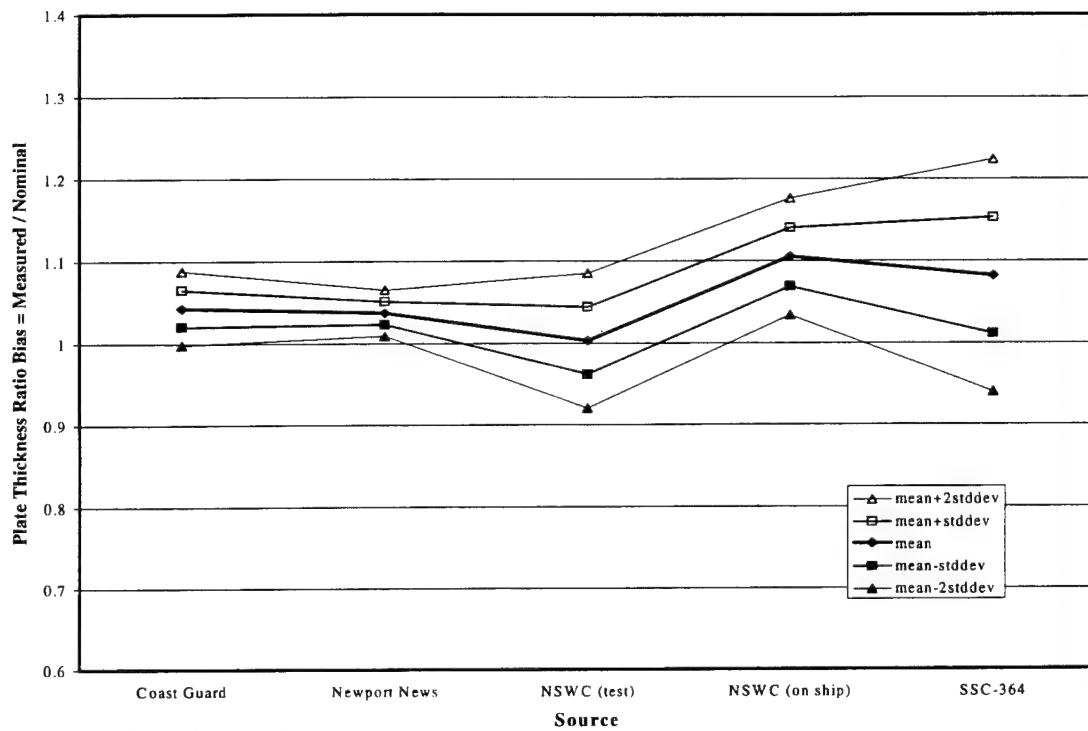
**FIGURE 3.4.3a.** The Plate Thickness Ratio Bias Versus the Source of the Data.
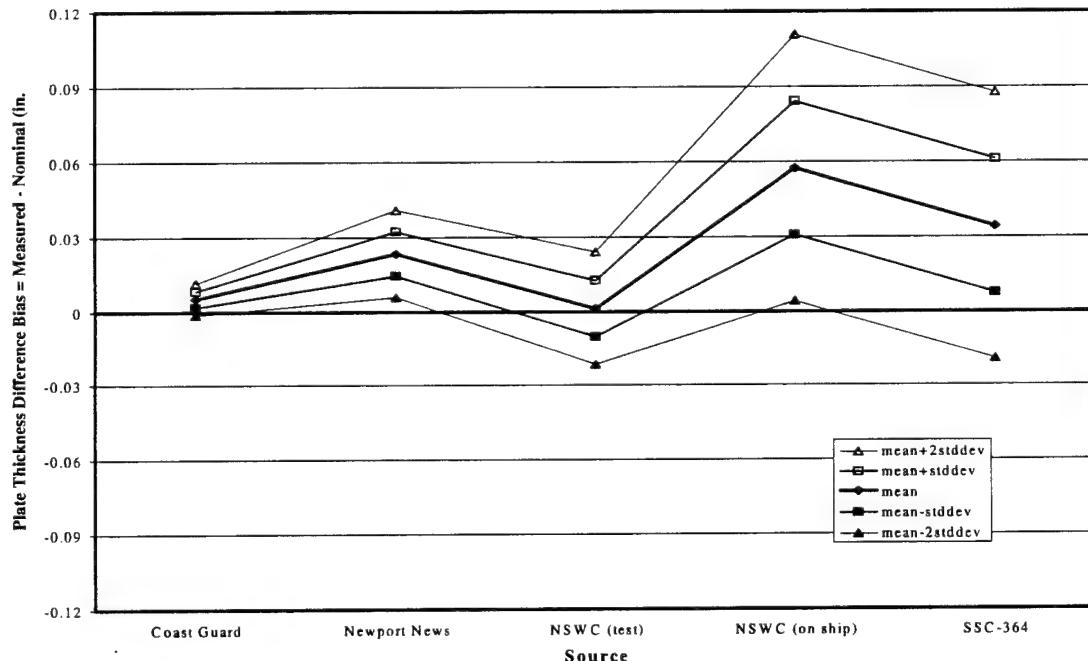


**FIGURE 3.4.3b.** The Plate Thickness Difference Bias Versus the Source of the Data.

*3.4.4  Effect of the Specification on Plate Thickness Bias*

The bias of the plate thickness appears to be influenced by the manner in which it is ordered. As the US Navy pays for material based on its weight, it benefits the manufacturer to allow the thickness to be skewed toward the higher tolerance limit. The opposite would be the case for customers who order per piece, where the minimum amount of material necessary would be used and the plate thickness would tend to be closer to the specified tolerance lower bound. The influence of specification may also be due to measurement methods and conditions such as whether the data are from a built and painted structure (as is the case with the Navy and commercial data) or from material measured before fabrication.

**Table 3.4.4a.** Plate thickness ratio bias classed by the manufacturing specification.

| Specification | Mean Ratio Bias | Standard Deviation | c.o.v. (%) | Number of Samples |
|---|---|---|---|---|
| ASTM | 1.002633 | 0.041217 | 4.111 | 239 |
| US Navy | 1.100096 | 0.12314 | 11.194 | 708 |
| Coast Guard | 1.042894 | 0.022506 | 2.158 | 1237 |
| Commercial/MSC | 1.021047 | 0.027795 | 2.722 | 69 |

**Table 3.4.4b.** Plate thickness difference bias classed by the manufacturing specification.

| Specification | Mean Difference Bias (in.) | Standard Deviation (in.) | c.o.v. (%) | Number of Samples |
|---|---|---|---|---|
| ASTM | 0.001126 | 0.011385 | 1008 | 239 |
| US Navy | 0.036178 | 0.024836 | 68.7 | 708 |
| Coast Guard | 0.005078 | 0.003274 | 64.4 | 1237 |
| Commercial/MSC | 0.015884 | 0.021588 | 136 | 69 |
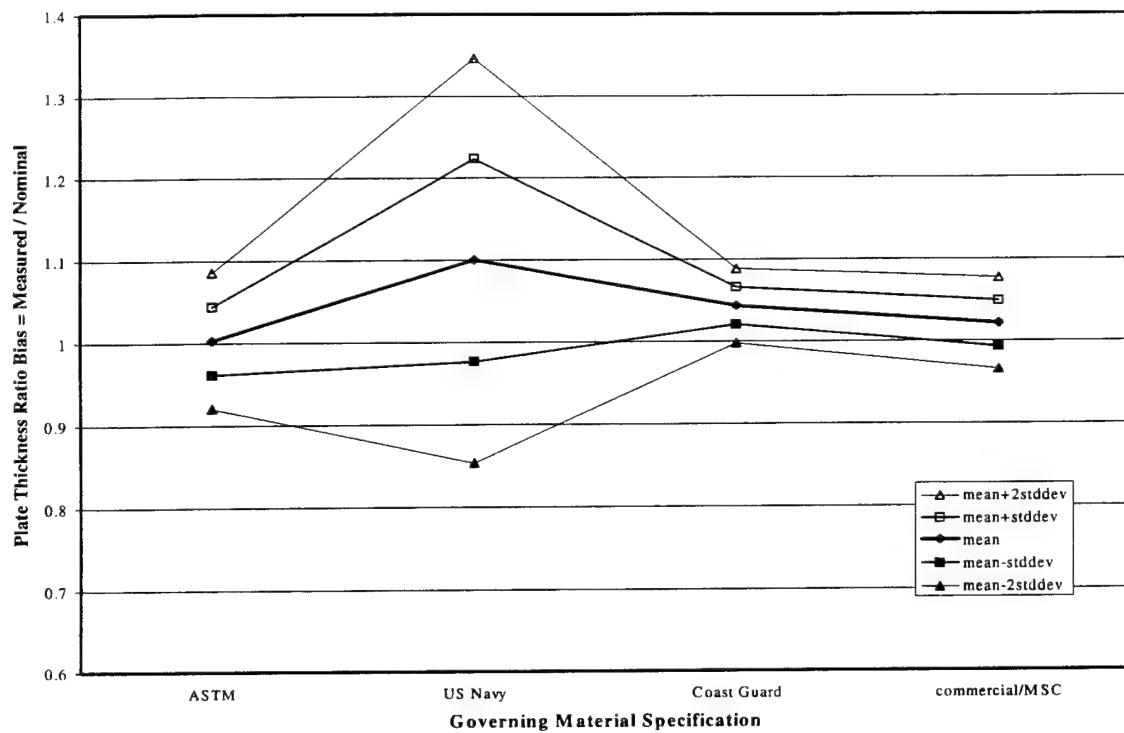
**FIGURE 3.4.4a.** The plate thickness ratio bias plotted against the material specification.
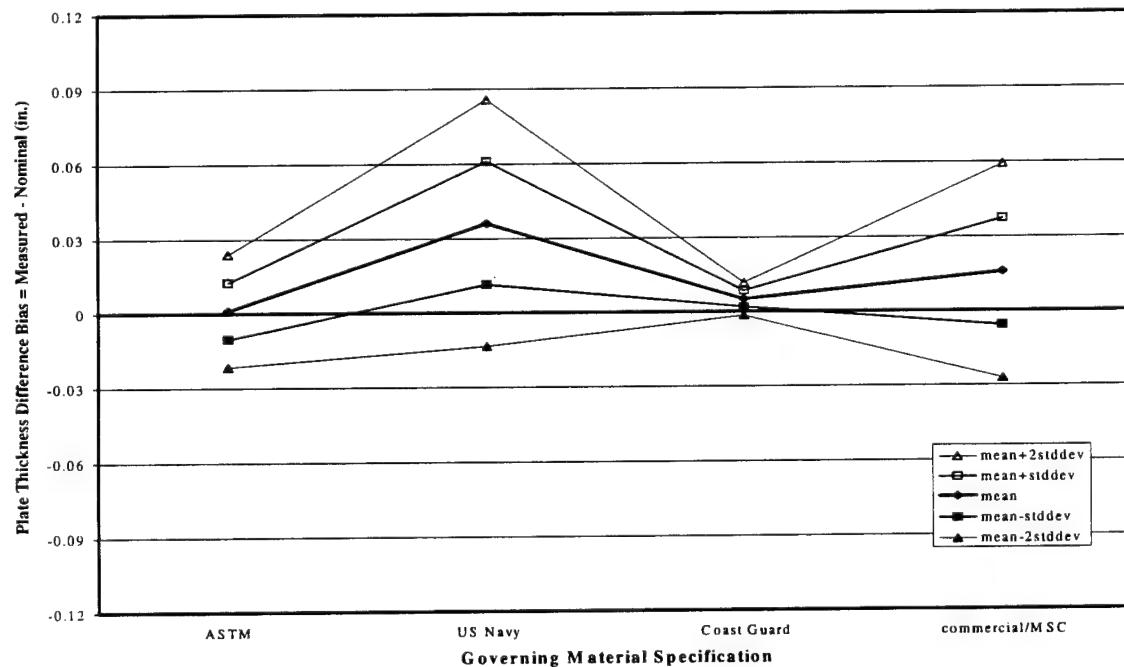


**FIGURE 3.4.4b.** The plate thickness difference bias plotted against the material specification.

### 3.4.5 Effect of Measurement Technique on Plate Thickness Bias

The techniques used in gathering the data depended on access to the material. If a free edge of the plate was accessible, a micrometer can be used. If the plate is part of an existing structure, without an accessible free edge or opening, ultrasonic techniques (UT) are the only option. The NSWC on-board ship data were obtained through the use of UT. Micrometers and UT were both used to find thicknesses of plating prior to construction. The influence of the conditions under which the measurements were taken may have an impact on the results shown in Tables 3.4.5a and 3.4.5b.

**Table 3.4.5a.** Plate thickness ratio bias classed by measurement technique.

| Measurement Technique | Mean Ratio Bias | Standard Deviation | c.o.v. (%) | Number of Samples |
|---|---|---|---|---|
| Micrometer | 1.036208 | 0.029082 | 2.807 | 1631 |
| Ultrasonic | 1.107090 | 0.130003 | 11.743 | 622 |

**Table 3.4.5b.** Plate thickness difference bias classed by measurement technique.

| Measurement Technique | Mean Difference Bias (in.) | Standard Deviation (in.) | c.o.v. (%) | Number of Samples |
|---|---|---|---|---|
| Micrometer | 0.006183 | 0.008174 | 132.2 | 1631 |
| Ultrasonic | 0.037261 | 0.027019 | 72.5 | 622 |

### 3.4.6 Effect of a Surface Coating on Plate Thickness Bias

The correlation between the measurement technique and the presence of a surface coating as shown in Table 3.4 is also apparent if one compares Tables 3.4.5a and 3.4.6a and Tables 3.4.5b and 3.4.6b. The influence of paint on the measured plate thickness when ultrasonic techniques are used is unknown. The bias is noticeably higher as is the associated uncertainty.

**Table 3.4.6a.** Plate thickness ratio bias classed by presence of surface coating.

| Surface Treatment | Mean Ratio Bias | Standard Deviation | c.o.v. (%) | Number of Samples |
|---|---|---|---|---|
| Not Coated | 1.020186 | 0.034588 | 3.390 | 478 |
| Coated | 1.117579 | 0.136604 | 12.223 | 561 |

**Table 3.4.6b.** Plate thickness difference bias classed by presence of surface coating.

| Surface Treatment | Mean Ratio Bias (in.) | Standard Deviation (in.) | c.o.v. (%) | Number of Samples |
|---|---|---|---|---|
| Not Coated | 0.012230 | 0.015064 | 123 | 478 |
| Coated | 0.039169 | 0.027818 | 71 | 561 |

*3.4.7 Effect of Plate Deformation on Plate Thickness Bias*

Thickness measurements of plating may be influenced by the proximity of the measurement to regions of large displacement as may result from collision or other extreme loads (as in the SSC-364 data). Wave slap deformation is smoother and probably less prone to changing the local thickness. The presence of deformation is highly correlated to the data source and may not have any influence on the bias or uncertainty.

**Table 3.4.7a.** Plate thickness ratio bias classed presence of deformation.

| Local Deformation? | Mean Ratio Bias | Standard Deviation | c.o.v. (%) | Number of Samples |
|---|---|---|---|---|
| No | 1.049872 | 0.079510 | 7.573 | 1833 |
| Yes | 1.081260 | 0.072527 | 6.708 | 420 |

**Table 3.4.7b.** Plate thickness difference bias classed presence of deformation.

| Local Deformation? | Mean Difference Bias (in.) | Standard Deviation (in.) | c.o.v. (%) | Number of Samples |
|---|---|---|---|---|
| No | 0.010312 | 0.016557 | 62.3 | 1833 |
| Yes | 0.034186 | 0.026765 | 78.3 | 420 |

## 3.5. Probability Density Functions Representing Plate Thickness Bias

The union of all sample sets was analyzed using both the ratio bias and difference bias. Probability density functions were developed as discussed in Section 1.3.2.

### 3.5.1. Plate Thickness Ratio Bias

The bin size was chosen as 37 in order to achieve an adequate detail level, and to create the smoothest empirical distribution. The statistics and ranking of the p.d.f.'s are shown in Table 3.5.1 and the graphical comparisons of the analytical p.d.f. to the histograms are shown in Figure 3.5.1.

**TABLE 3.5.1.** Results from BestFit Program for Plate Thickness Ratio Bias.

|  | Beta | Extreme Value Type I | Logistic | Log-Logistic | Lognorm |
|---|---|---|---|---|---|
| Param 1 | 7.50564 | 1.02782 | 1.048487 | 0.9068 | 1.047963 |
| Param 2 | 44.5659 | 0.035805 | 0.025153 | 0.130719 | 0.044985 |
| Param 3 |  |  |  | 4.555227 |  |
| Adjust | +0.91 |  |  |  |  |
| Mean | 1.049985 | 1.048487 | 1.048487 | 1.048487 | 1.047963 |
| Mode | 1.035771 | 1.02782 | 1.048487 | 1.025319 | 1.045074 |
| Median | 1.045418 | 1.040943 | 1.048487 | 1.037519 | 1.046999 |
| Stnd Dev | 0.048213 | 0.045922 | 0.045622 | 0.062713 | 0.044985 |
| Variance | 2.32E-03 | 2.11E-03 | 2.08E-03 | 3.93E-03 | 2.02E-03 |
| Skewness | 0.546016 | 1.139547 | 0 | 1.600241 | 0.128858 |
| Kurtosis | 0.436843 | 5.4 | 4.2 | 7.347175 | 3.029534 |
| C-S Test | 4799.145 | 2.47E+06 | 1134.929 | 661.8386 | 2.15E+06 |
| C-S Rank | 5 |  | 2 | 1 |  |
| K-S Test | 0.155027 | 0.105293 | 0.154073 | 0.143526 | 0.154932 |
| K-S Rank |  | 1 | 5 | 2 |  |
| A-D Test | 55.36476 | 37.67449 | 42.50332 | 74.5443 | 51.14192 |
| A-D Rank |  | 1 | 2 |  | 5 |
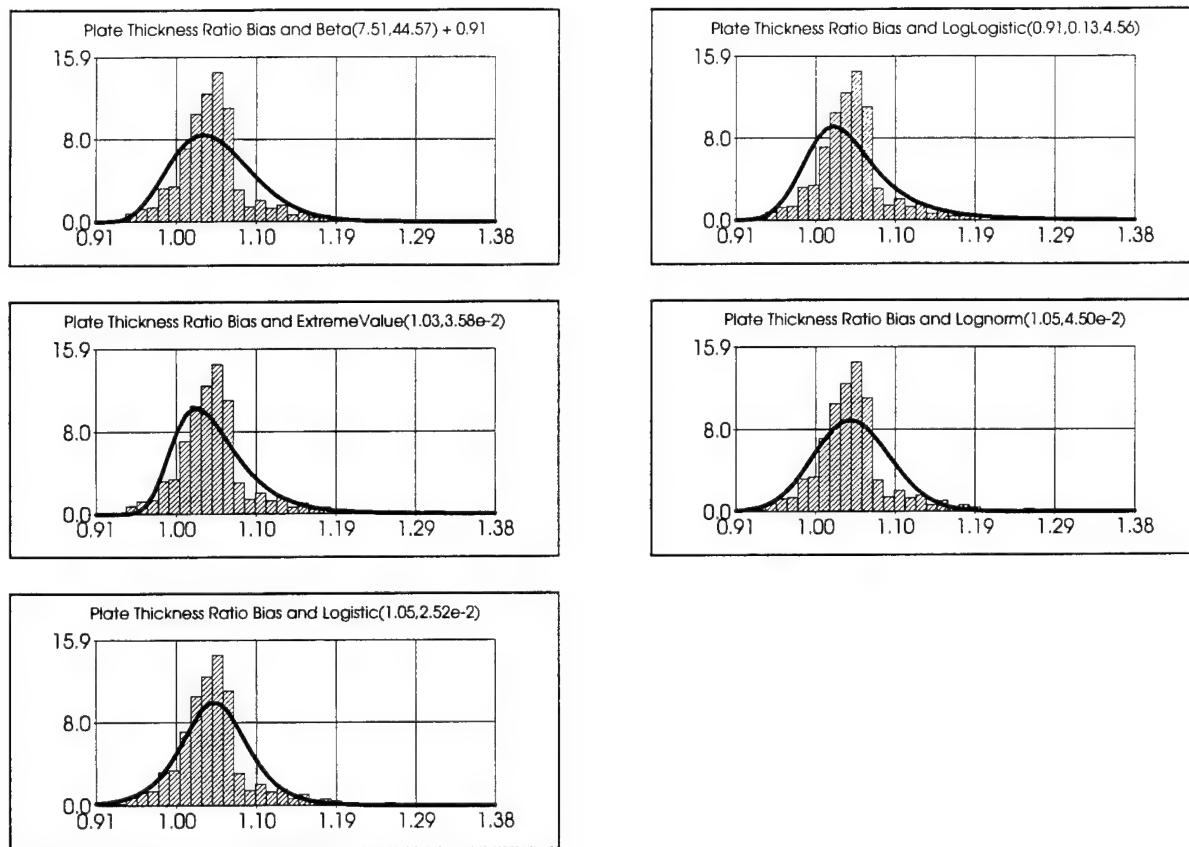
**FIGURE 3.5.1.** Plate Thickness Ratio Bias Distribution Fit with the Most Highly Ranked Probability Density Functions.

### 3.5.2. *Plate Thickness Difference Bias*

The bin size was chosen as 18, in order to achieve an adequate detail level, and to create the smoothest empirical distribution. The statistics and ranking of the p.d.f.'s are shown in Table 3.5.2 and the graphical comparisons of the analytical p.d.f. to the histograms are shown in Figure 3.5.2.

**TABLE 3.5.2.** Results from BestFit Program for Plate Thickness Difference Bias.

|  | Beta | Erlang | Extreme Value Type I | Gamma | Lognorm | Pearson VI |
|---|---|---|---|---|---|---|
| Param 1 | 3.11834 | 4 | 6.17E-03 | 4.313557 | 0.03898 | 22.02591 |
| Param 2 | 78.87023 | 8.90E-03 | 0.013732 | 8.82E-03 | 0.022264 | 6.04912 |
| Param 3 |  |  |  |  |  | 8.83E-03 |
| Adjust | -0.0233 | -0.0233 |  | -0.0233 | -0.0233 | -0.0233 |
| Mean | 0.014732 | 0.012307 | 0.014096 | 0.014732 | 0.015678 | 0.015198 |
| Mode | 3.18E-03 | 3.41E-03 | 6.17E-03 | 5.92E-03 | 2.22E-03 | 3.02E-03 |
| Median | 0.011031 | 9.39E-03 | 0.011203 | 0.011837 | 0.010546 | 0.010173 |
| Std Dev | 0.020997 | 0.017804 | 0.017612 | 0.018313 | 0.022264 | 0.021213 |
| Variance | 4.41E-04 | 3.17E-04 | 3.10E-04 | 3.35E-04 | 4.96E-04 | 4.50E-04 |
| Skewness | 1.047838 | 1 | 1.139547 | 0.962969 | 1.899846 | 1.817592 |
| Kurtosis | 4.523 | 4.5 | 5.4 | 4.391 | 10.036 | 7.724 |
| C-S Test | 1153.9 | 1315.4 | 936.2 | 1126.5 | 899.9 | 9678.5 |
| C-S Rank | 5 |  | 2 | 3 | 1 |  |
| K-S Test | 0.17852 | 0.18630 | 0.19250 | 0.20026 | 0.16862 | 0.16649 |
| K-S Rank | 3 | 4 | 5 |  | 2 | 1 |
| A-D Test | 128.6 | 116.4 | 105.9 | 119.3 | 101.7 | 81.5 |
| A-D Rank |  | 4 | 3 | 5 | 2 | 1 |
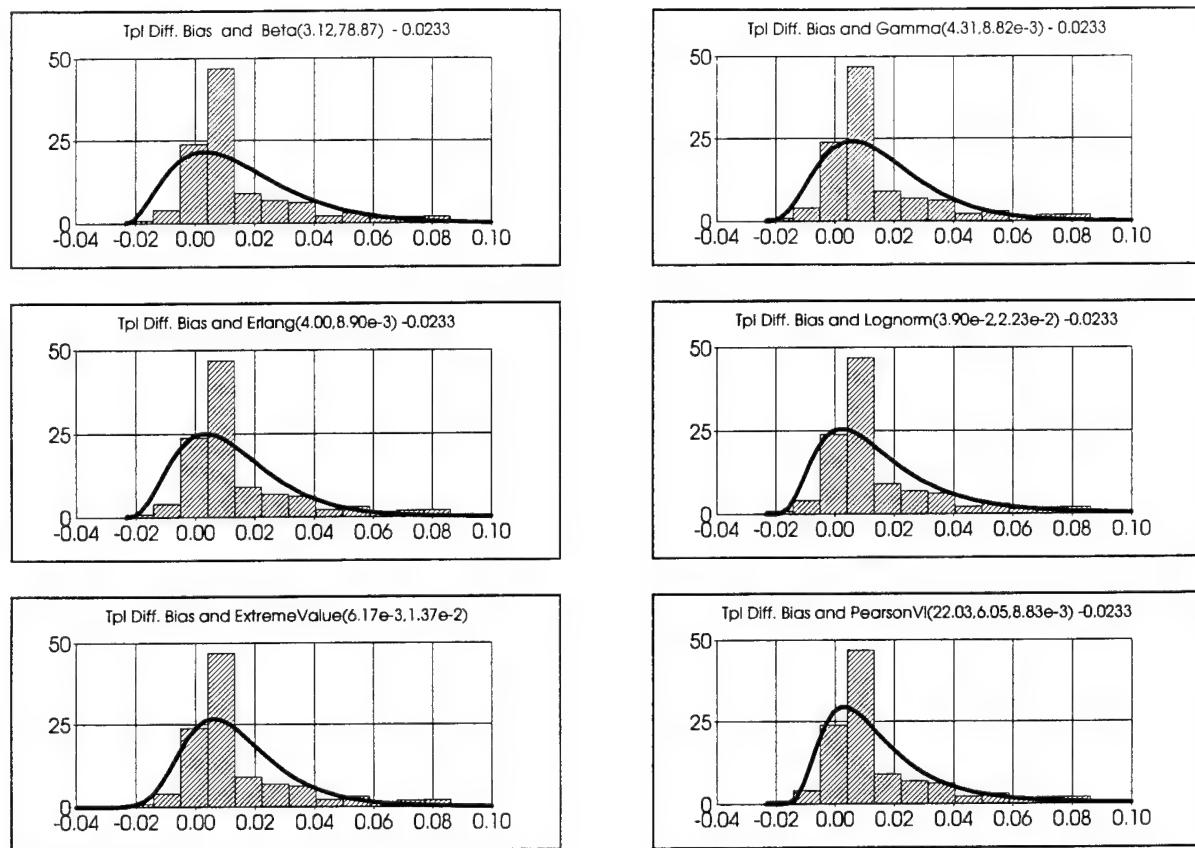
**FIGURE 3.5.2.** Plate Thickness Difference Bias Distribution Fit with the Most Highly Ranked Probability Density Functions.

## 4.0 Stiffener Dimensions

### 4.1 Introduction

Stiffener geometry includes length, spacing, web height, web thickness, flange breadth, and flange thickness. The stiffener cross-sectional properties (web and flange dimensions) are dependent upon the supplier's tolerances, while the length and spacing are a result of construction techniques. Stiffeners are manufactured by either cutting an I-beam or channel to the desired size of tee or angle stiffener, or building the stiffener from plating. Higher strength steels require the stiffener to be built up, while lower strength steels may be cold-rolled. The analysis which follows, lumps the various types together into one sample population. Future efforts may treat cold-rolled and built-up sections separately. The plate thickness statistics would then be applicable to the flange and web thicknesses of the section, and the flange breadth and web height could be considered the same as the cold-rolled values.

### 4.2 Stiffener Dimension Uncertainty Literature Survey

The steps necessary for estimating the c.o.v.'s of breadth of a flange and a depth of the web of a stiffener were outlined by Daidola and Basar (1980) as follows:

$$\text{COV}(b_f) = \frac{\sigma_{\Delta b_f}}{\overline{\Delta b_f} + b_{fn}} \text{ for flanges} \qquad (4\text{-}a)$$

or

$$\text{COV}(d_w) = \frac{\sigma_{\Delta d_*}}{\overline{\Delta d_w} + d_{wn}} \text{ for webs} \qquad (4\text{-}3b)$$

where $\sigma_\Delta$ = standard deviation of the difference bias in flange breadth or web depth, $\overline{\Delta}$ = difference bias mean value of flange breath or web depth, $b_f$ = flange breadth, $d_w$ = web depth, and the subscript $n$ = nominal or design value.

## 4.3 Stiffener Length

### 4.3.1 Stiffener Length Data

The stiffener length data were measured from current US Navy ships as discussed in Appendix C. Design values were garnered from drawings which did not always accurately correspond to the measured values. These extreme values were filtered out as they could not be explained by pure randomness. The statistics of the filtered data are shown in Table 4.3.1.

**TABLE 4.3.1.** Stiffener Length Data Statistical Analysis.

|  | Ratio Bias | Difference Bias (in.) |
|---|---|---|
| Mean | 0.98818 | -1.2640 |
| Standard Deviation | 0.04670 | 4.8189 |
| c.o.v. (%) | 4.726 | n/a |
| Standard Error | 0.004950 | 0.51080 |
| Median | 0.992021 | -0.50000 |
| Mode | 1 | 0 |
| Sample Variance | 0.002181 | 23.22184 |
| Kurtosis | 1.791666 | 0.69207 |
| Skewness | 0.787038 | 0.44651 |
| Range | 0.252315 | 21.5 |
| Minimum | 0.907407 | -10 |
| Maximum | 1.159722 | 11.5 |
| Count | 89 | 89 |
| Confidence Level (95.0%) | 0.009837 | 1.01511 |

### 4.3.2 *Stiffener Length Ratio Bias*

The stiffener length ratio bias was analyzed using bin sizes 4 and 6. The results from the bin size of 6 are shown below. The Lognormal distribution is recommended for use, with the Normal distribution being acceptable if an even simpler model is needed.

**TABLE 4.3.2.** Results from BestFit for Stiffener Length Ratio Bias.

|          | Beta     | Extreme Value Type I | Gamma    | Logistic | Lognorm  | Normal   |
|----------|----------|----------------------|----------|----------|----------|----------|
| Param 1  | 2.779396 | 0.97409              | 461.9836 | 0.994171 | 0.988161 | 0.988171 |
| Param 2  | 27.13123 | 0.042155             | 2.14E-03 | 0.027699 | 0.045801 | 0.046701 |
| Param 3  |          |                      |          |          |          |          |
| Adjust   | +0.91    |                      |          |          |          |          |
| Mean     | 1.000302 | 0.998422             | 0.990142 | 0.994171 | 0.988161 | 0.988171 |
| Mode     | 0.971132 | 0.97409              | 0.987999 | 0.994171 | 0.984985 | 0.988171 |
| Median   | 0.991282 | 0.98954              | 0.989428 | 0.994171 | 0.987101 | 0.988171 |
| Stnd Dev | 0.052219 | 0.054065             | 0.046066 | 0.05024  | 0.045801 | 0.046701 |
| Variance | 2.73E-03 | 2.92E-03             | 2.12E-03 | 2.52E-03 | 2.10E-03 | 2.18E-03 |
| Skewness | 0.97717  | 1.139547             | 0.09305  | 0        | 0.13915  | 0        |
| Kurtosis | 4.551896 | 5.4                  | 3.012987 | 4.2      | 3.034442 | 3        |
| C-S Test | 25.74651 | 26.10032             | 29.4929  | 25.76272 | 30.67955 | 32.54448 |
| C-S Rank | 1        | 3                    |          | 2        |          |          |
| K-S Test | 0.246326 | 0.229794             | 0.217709 | 0.2542   | 0.198648 | 0.208504 |
| K-S Rank |          |                      | 3        |          | 1        | 2        |
| A-D Test | 10.79478 | 4.423916             | 3.507111 | 4.3701   | 3.256597 | 3.43286  |
| A-D Rank |          |                      | 3        |          | 1        | 2        |
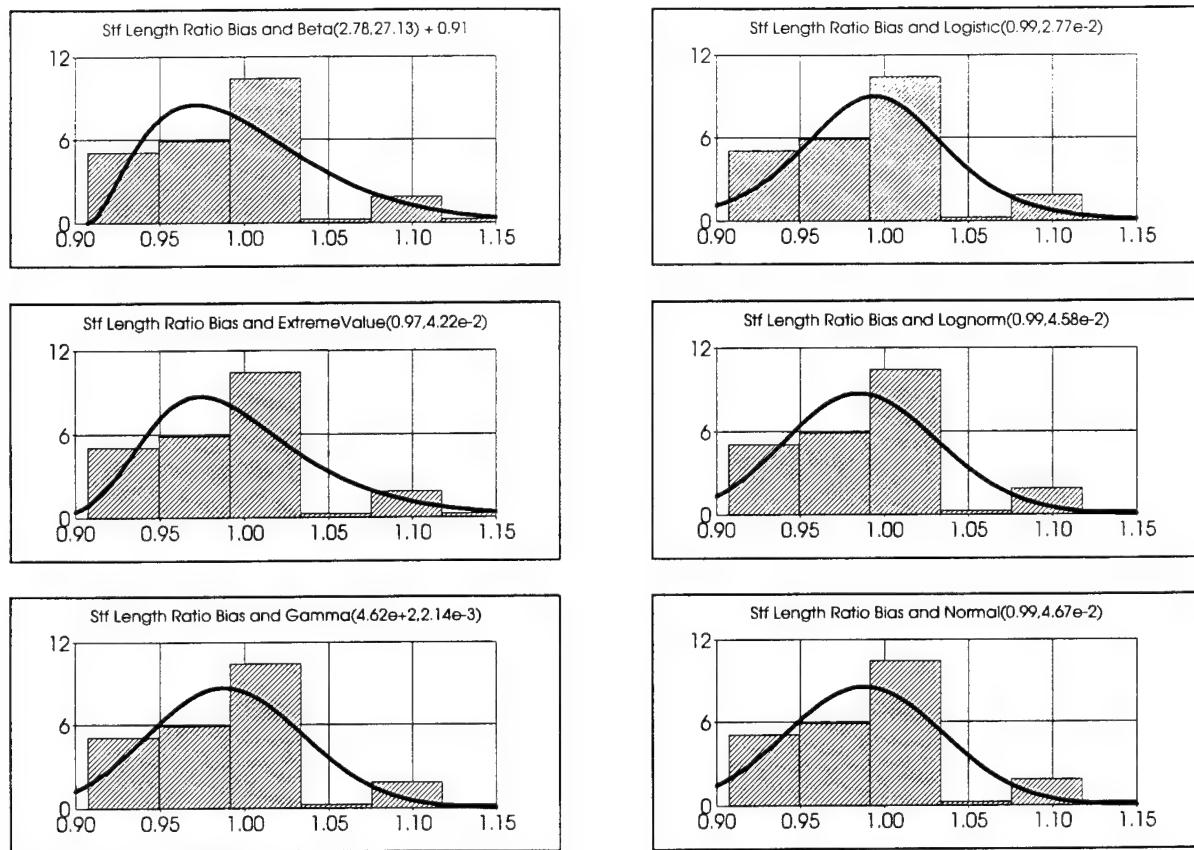
**FIGURE 4.3.2.** Stiffener Length Ratio Bias Distribution Fit with the Most Highly Ranked Probability Density Functions.

### 4.3.3 Stiffener Length Difference Bias

The stiffener length difference bias was analyzed using bin sizes of 4, 5 and 6. The results from the bin size of 6 are shown below. The Logistic distribution is recommended due to the high ranking by the goodness-of-fit tests. For simplicity, the Normal distribution may be used.

**TABLE 4.3.3.** Results from BestFit for Stiffener Length Difference Bias (inches).

|          | Chisq    | Extreme Value Type I | Logistic | Normal   | Rayleigh | Triang   |
|----------|----------|----------------------|----------|----------|----------|----------|
| Param 1  | 9        | -3.43279             | -1.26405 | -1.26405 | 7.047334 | -10.003  |
| Param 2  |          | 3.757284             | 2.639422 | 4.818904 |          | -2.16585 |
| Param 3  |          |                      |          |          |          | 11.50298 |
| Adjust   | -10.0    |                      |          |          | -10.0    |          |
| Mean     | -1.00298 | -1.26405             | -1.26405 | -1.26405 | -1.17045 | -0.22195 |
| Mode     | -3.00298 | -3.43279             | -1.26405 | -1.26405 | -2.95564 | -2.16585 |
| Median   | -1.66014 | -2.05569             | -1.26405 | -1.26405 | -1.70537 | -0.62058 |
| Stnd Dev | 4.242641 | 4.818904             | 4.787383 | 4.818904 | 4.616965 | 3.922776 |
| Variance | 18       | 23.22184             | 22.91903 | 23.22184 | 21.31637 | 15.38817 |
| Skewness | 0.942809 | 1.139547             | 0        | 0        | 0.631111 | 0.252948 |
| Kurtosis | 4.333333 | 5.4                  | 4.2      | 3        | 3.245089 | 2.387877 |
| C-S Test | 57.93468 | 48.96781             | 50.50195 | 57.24968 | 51.80185 | 46.2253  |
| C-S Rank |          | 2                    | 3        |          |          | 1        |
| K-S Test | 0.20345  | 0.235385             | 0.203097 | 0.219386 | 0.202464 | 0.273466 |
| K-S Rank | 3        |                      | 2        |          | 1        |          |
| A-D Test | 15.05583 | 5.100305             | 3.444566 | 3.80533  | 7.841941 | 10.31328 |
| A-D Rank |          | 3                    | 1        | 2        |          |          |
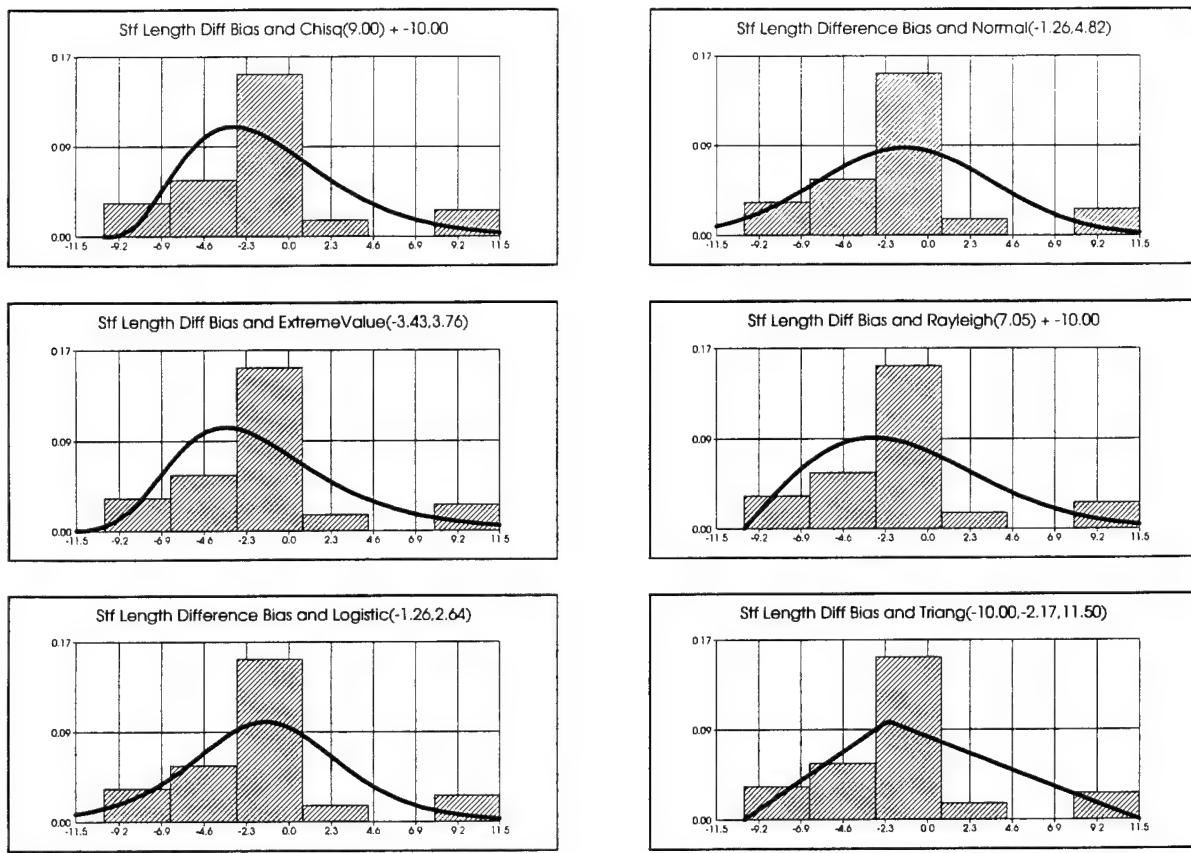
**FIGURE 4.3.3.** Stiffener Length Difference Bias (inches) Distribution Fit with the Most Highly Ranked Probability Density Functions.

## 4.4  Stiffener Spacing

### 4.4.1  Stiffener Spacing Data

The stiffener spacing data were collected from current US Navy ships as discussed in Appendix C.  The data are primarily from bulkheads and decks;  which is due to the irregularity of the spacing on the sideshell,  and the lack of accessible regions to survey.  The measurements were taken from flange edge to flange edge.  This method does not reflect the effects of stiffener distortion or flange tilting.  The nominal value of the spacing was taken from design drawings.

**TABLE 4.4.1.**  Stiffener Spacing Data Statistical Analysis.

|  | Ratio Bias | Difference Bias (in.) |
|---|---|---|
| Mean | 0.99216 | -0.2514 |
| Standard Deviation | 0.02816 | 0.8669 |
| c.o.v. (%) | 2.838 | n/a |
| Standard Error | 0.001743 | 0.05366 |
| Median | 0.996875 | -0.18750 |
| Mode | 1 | 0 |
| Sample Variance | 0.000793 | 0.75159 |
| Kurtosis | 6.053459 | 6.04226 |
| Skewness | -0.931253 | -0.61868 |
| Range | 0.233333 | 8.25 |
| Minimum | 0.861979 | -4.4375 |
| Maximum | 1.095313 | 3.8125 |
| Count | 261 | 261 |
| Confidence Level (95.0%) | 0.003432 | 0.105668 |

## 4.4.2 Stiffener Spacing Ratio Bias

The stiffener spacing ratio bias was analyzed using bin sizes of 14 and 29 resulting in a close agreement. The results from the bin size of 14 are shown below in Table 4.4.2, and the plots of the p.d.f.'s with the data histogram are shown in Figure 4.4.2. The Logistic distribution is ranked highly by all three goodness-of-fit methods. Should simplicity be needed, the Normal distribution may provide an adequate description of the bias.

**TABLE 4.4.2.** Results from BestFit for Stiffener Spacing Ratio Bias.

|  | Gamma | Logistic | Normal | Triang | Uniform |
|---|---|---|---|---|---|
| Param 1 | 1220.72 | 0.9922 | 0.9922 | 0.8615 | 0.8615 |
| Param 2 | 8.13E-04 | 0.01542 | 0.02816 | 1.00365 | 1.09581 |
| Param 3 |  |  |  | 1.09581 |  |
| Adjust |  |  |  |  |  |
| Mean | 0.9922 | 0.9922 | 0.9922 | 0.9870 | 0.9787 |
| Mode | 0.9914 | 0.9922 | 0.9922 | 1.00365 | 0.8615 |
| Median | 0.9919 | 0.9922 | 0.9922 | 0.9905 | 0.9787 |
| Stnd Dev | 0.028397 | 0.027972 | 0.028157 | 0.09553 | 0.067642 |
| Variance | 8.06E-04 | 7.82E-04 | 7.93E-04 | 9.13E-03 | 4.58E-03 |
| Skewness | 0.057243 | 0 | 0 | -0.20242 | 0 |
| Kurtosis | 3.00492 | 4.2 | 3 | 2.3879 | 1.8 |
| C-S Test | 3124.52 | 188.70 | 1889.17 | 299.78 | 785.23 |
| C-S Rank |  | 1 |  | 2 | 3 |
| K-S Test | 0.1888 | 0.1712 | 0.1845 | 0.2626 | 0.3546 |
| K-S Rank | 3 | 1 | 2 |  |  |
| A-D Test | 17.936 | 14.397 | 17.450 | 35.153 | 57.446 |
| A-D Rank | 3 | 1 | 2 |  |  |
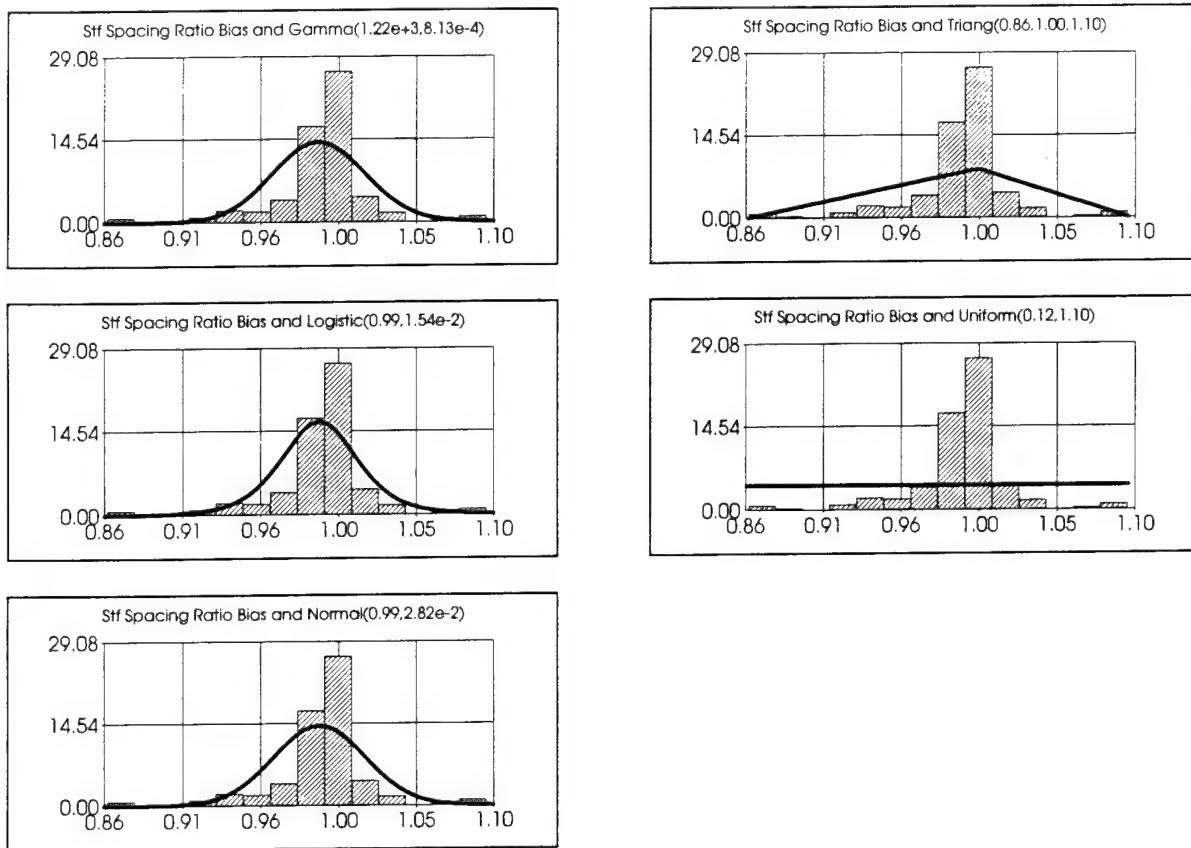
**FIGURE 4.4.2.** Stiffener Spacing Ratio Bias Distribution Fit with the Most Highly Ranked Probability Density Functions.

### 4.4.3 Stiffener Spacing Difference Bias

The stiffener spacing difference bias was analyzed using bin sizes of 14 and 25 with good agreement in the results. The BestFit program results from bin size of 14 are shown in Table 4.4.3, and plots of the distributions overlaid on the histogram are shown in Figure 4.4.3. Like the ratio bias, the Logistic distribution is recommended as all three goodness-of-fit methods ranked it highest. The Normal distribution is an acceptable substitute for simple applications.

**TABLE 4.4.3.** Results from BestFit for Stiffener Spacing Difference Bias (inches).

|          | Beta       | Logistic | Normal  | Rayleigh | Triang   |
|----------|------------|----------|---------|----------|----------|
| Param 1  | 12.1736    | -0.2514  | -0.2514 | 3.1688   | -4.6484  |
| Param 2  | 11.8355    | 0.47484  | 0.8669  |          | -0.01786 |
| Param 3  |            |          |         |          | 4.0235   |
| Adjust   | *8.67-4.65 |          |         | -4.65    |          |
| Mean     | -0.2514    | -0.2514  | -0.2514 | -0.6770  | -0.2143  |
| Mode     | -0.2459    | -0.2514  | -0.2514 | -1.4797  | -0.01786 |
| Median   | -0.2497    | -0.2514  | -0.2514 | -0.9175  | -0.1676  |
| Stnd Dev | 0.86694    | 0.86127  | 0.86694 | 2.07598  | 1.39370  |
| Variance | 0.75159    | 0.74179  | 0.75159 | 4.30970  | 1.94238  |
| Skewness | -0.01083   | 0        | 0       | 0.6311   | -0.0661  |
| Kurtosis | 2.8671     | 4.2      | 3       | 3.2451   | 2.3880   |
| C-S Test | 5.72E+05   | 110.55   | 675.37  | 640.52   | 401.15   |
| C-S Rank |            | 1        |         | 3        | 2        |
| K-S Test | 0.1982     | 0.1805   | 0.1956  | 0.3963   | 0.2917   |
| K-S Rank | 3          | 1        | 2       |          |          |
| A-D Test | 15.676     | 11.397   | 14.603  | 59.863   | 39.263   |
| A-D Rank | 3          | 1        | 2       |          |          |
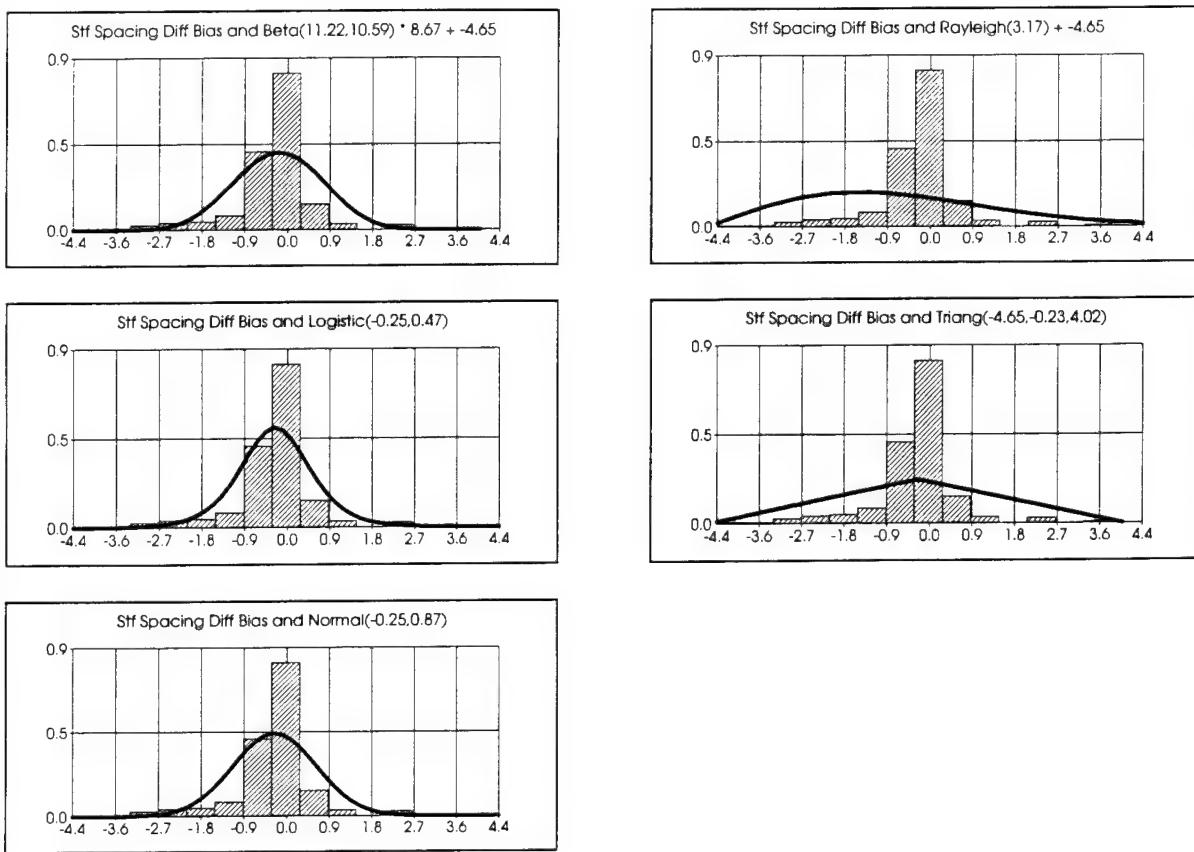
**FIGURE 4.4.3.** Stiffener Spacing Difference Bias (inches) Distribution Fit with the Most Highly Ranked Probability Density Functions.

## 4.5 Stiffener Depth

### 4.5.1 Stiffener Depth Data

The measurements by NAVSSES of the height of the stiffeners on board ships were conducted by measuring the height of the stiffener flange from the supporting plate. A pair of measurements were done on both flange edges, at three locations on each stiffener. The average of each pair of measurements is used to represent one data point. The resulting data set may be affected by localized distortion in the plating, tilting of the stiffener web and flange, and variations in the surface coating.

The data set as analyzed contains 547 points. Three extreme data points were filtered out of the analysis as they appear to be the result of inaccurate nominal values. The statistics of the data are summarized in Table 4.5.1.

**TABLE 4.5.1.** Stiffener Depth Data Statistical Analysis.

|  | Ratio Bias | Difference Bias (in.) |
|---|---|---|
| Mean | 0.99545 | -0.0281 |
| Standard Deviation | 0.01859 | 0.1171 |
| c.o.v. (%) | 1.867 | n/a |
| Standard Error | 0.000795 | 0.00501 |
| Median | 0.996835 | -0.01625 |
| Mode | 1.003125 | 0.015625 |
| Sample Variance | 0.000346 | 0.01371 |
| Kurtosis | 1.620069 | 8.99368 |
| Skewness | -0.347515 | -1.43248 |
| Range | 0.134510 | 1.25 |
| Minimum | 0.935310 | -0.84 |
| Maximum | 1.069820 | 0.41 |
| Count | 547 | 547 |
| Confidence Level (95.0%) | 0.001561 | 0.00983 |

### 4.5.2  Stiffener Depth Ratio Bias

BestFit was used to analyze the data using bin sizes of 10, 14 and 27, with the results of bin size 10 being used to show the results.  The analysis of the data using bin sizes 14 and 27 lead to the same conclusions as are found for data partitioned in 10 bins.  Table 4.5.2 shows the ranking associated with each goodness-of-fit method.  As all three methods rank the Logistic p.d.f. as the first choice,  it is recommended when representing the variability of the stiffener depth ratio bias.  Figure 4.5.2 shows each of the five distributions overlaid on the stiffener depth ratio bias histogram.  The reader may decide that the Normal distribution is more appropriate to use than the Logistic distribution for some purposes.

**TABLE 4.5.2.**  Results from BestFit for Stiffener Depth Ratio Bias.

|          | Erlang   | Extreme Value Type I | Gamma    | Logistic | Normal   |
|----------|----------|----------------------|----------|----------|----------|
| Param 1  | 2858     | 0.989431             | 2858.531 | 0.995454 | 0.995454 |
| Param 2  | 3.48E-04 | 0.015268             | 3.48E-04 | 0.010182 | 0.018589 |
| Param 3  |          |                      |          |          |          |
| Adjust   |          |                      |          |          |          |
| Mean     | 0.995269 | 0.998244             | 0.995454 | 0.995454 | 0.995454 |
| Mode     | 0.994921 | 0.989431             | 0.995106 | 0.995454 | 0.995454 |
| Median   | 0.995153 | 0.995027             | 0.995338 | 0.995454 | 0.995454 |
| Stnd Dev | 0.018617 | 0.019582             | 0.018619 | 0.018467 | 0.018589 |
| Variance | 3.47E-04 | 3.83E-04             | 3.47E-04 | 3.41E-04 | 3.46E-04 |
| Skewness | 0.037411 | 1.139547             | 0.037407 | 0        | 0        |
| Kurtosis | 3.002099 | 5.4                  | 3.002099 | 4.2      | 3        |
| C-S Test | 103.3228 | 6.43E+07             | 104.1572 | 54.79971 | 99.35768 |
| C-S Rank | 3        |                      |          | 1        | 2        |
| K-S Test | 0.114371 | 0.103826             | 0.110674 | 0.091427 | 0.108476 |
| K-S Rank |          | 2                    |          | 1        | 3        |
| A-D Test | 9.237065 | 25.75238             | 9.010445 | 5.537266 | 8.673076 |
| A-D Rank |          |                      | 3        | 1        | 2        |
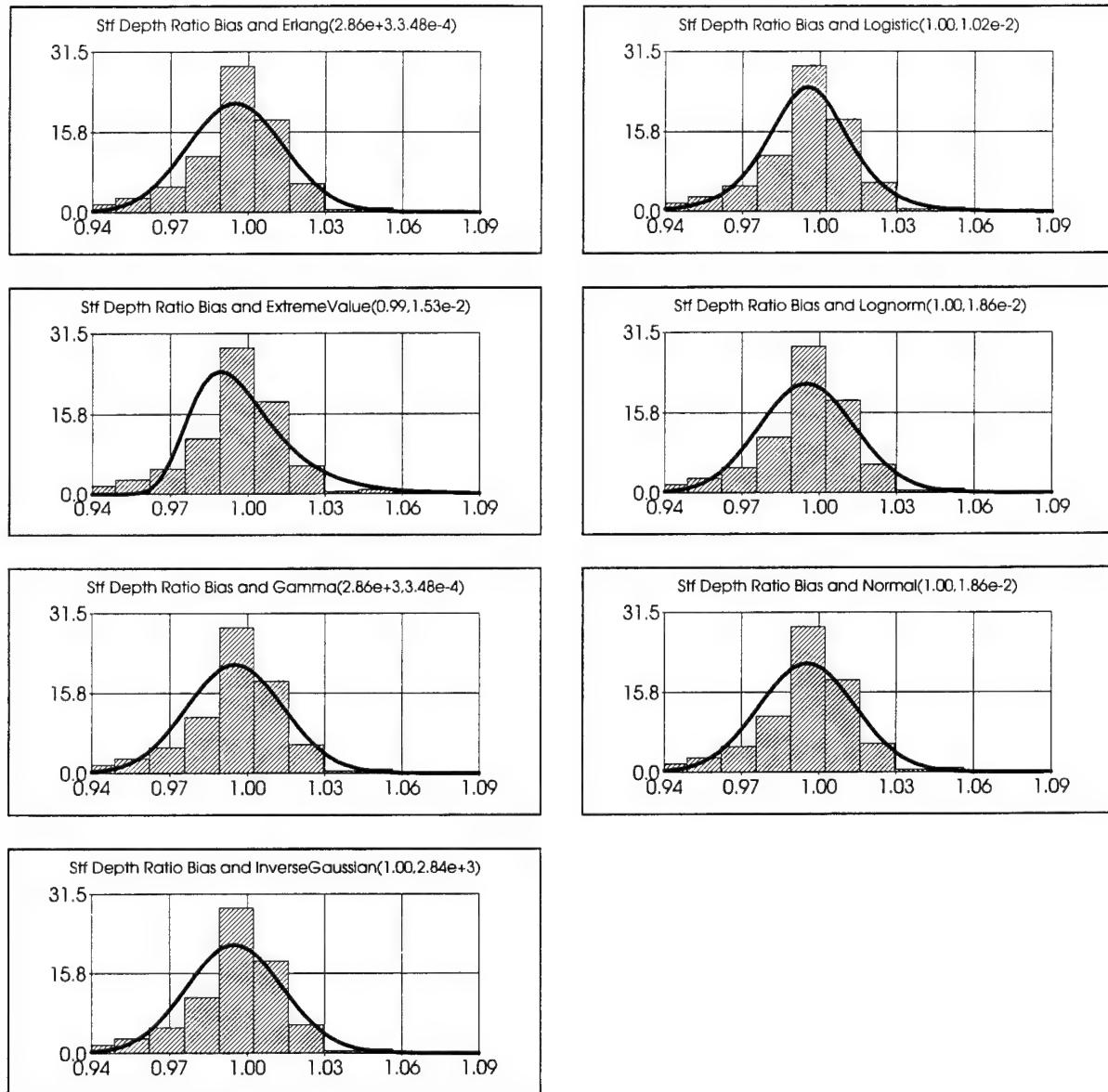
**FIGURE 4.5.2.** Stiffener Depth Ratio Bias Distribution Fit with the Most Highly Ranked Probability Density Functions.

*4.5.3 Stiffener Depth Difference Bias*

The stiffener depth difference bias was analyzed using bin sizes of 22 and 40, with the results of bin size 22 being used to show the results in Table 4.5.3, and the plots in Figure 4.5.3. As with the ratio bias, the recommended p.d.f. for the difference bias is the Logistic distribution. The Normal distribution provides a better match of statistics, and may be appropriate for most purposes.

**TABLE 4.5.3.** Results from BestFit for Stiffener Depth Difference Bias (inches).

|          | Beta       | Logistic  | Normal    | Rayleigh  | Triang    | Weibull   |
|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Param 1  | 26.12527  | -0.02812  | -0.02812  | 0.701985  | -1.01397  | 9.574818  |
| Param 2  | 16.1526   | 0.064127  | 0.11708   |           | 0.023891  | 1.034088  |
| Param 3  |           |           |           |           | 0.583965  |           |
| Adjust   | *1.60-1.01 |          |           | -1.01     |           | -1.01     |
| Mean     | -0.02654  | -0.02812  | -0.02812  | -0.13416  | -0.13537  | -0.03202  |
| Mode     | -0.01718  | -0.02812  | -2.81E-02 | -0.31198  | 0.023891  | 8.28E-03  |
| Median   | -0.02354  | -0.02812  | -0.02812  | -0.18744  | -0.10336  | -0.01871  |
| Stnd Dev | 0.118022  | 0.116314  | 0.11708   | 0.459896  | 0.226048  | 0.12308   |
| Variance | 0.013929  | 0.013529  | 0.013708  | 0.211504  | 0.051098  | 0.015149  |
| Skewness | -0.14426  | 0         | 0         | 0.631111  | -0.27627  | -0.57645  |
| Kurtosis | 7.25016   | 4.2       | 3         | 3.245089  | 2.387843  | 3.252494  |
| C-S Test | 2.77E+10  | 1702.891  | 2.00E+08  | 1669.946  | 863.6804  | 28806.8   |
| C-S Rank |           | 3         |           | 2         | 1         |           |
| K-S Test | 0.09353   | 0.083329  | 0.099285  | 0.430123  | 0.341009  | 0.094464  |
| K-S Rank | 2         | 1         |           |           |           | 3         |
| A-D Test | 8.118197  | 4.403559  | 7.900682  | 159.4432  | 109.9169  | 8.122161  |
| A-D Rank | 3         | 1         | 2         |           |           | 4         |
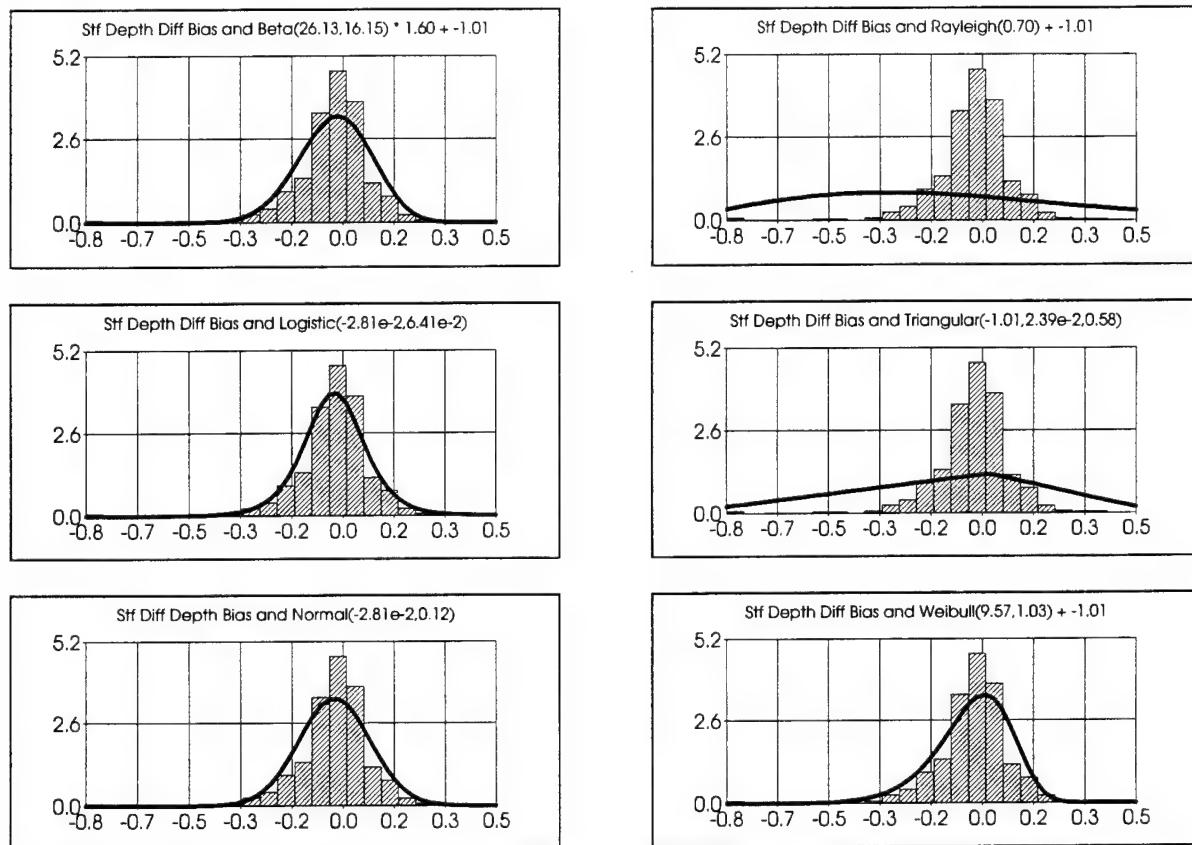
**FIGURE 4.5.3.** Stiffener Depth Difference Bias (inches) Distribution Fit with the Most Highly Ranked Probability Density Functions.

## 4.6 Web Thickness

### 4.6.1 Stiffener Web Thickness Data

The ease of access to the stiffener webs influenced whether they were measured using ultrasound techniques or a micrometer. The measurement method was not notated on the data collection sheets. Some of the samples were found to vary quite a bit from the thickness specified in the stiffener catalog. As the discontinuity in the frequency density was quite pronounced, these points were filtered out of the final analysis. An example of this would be a 5x4x6#T stiffener from the CG-47 whose web was measured to be 0.134 in. thick, but whose nominal value is 0.190 in. The converse also occurs with measured values being 50% greater than the specified value. Such disparity was not seen in the other dimensions (height, flange breadth, and flange thickness) on the same stiffeners. As these stiffeners were designed to be rolled sections, there may be another explanation besides pure randomness in the thickness. The amount of paint covering the sample is an unknown quantity, but would tend to skew the bias upward. (Please look in Appendix C for discussion of the methods used for measurement.)

**TABLE 4.6.1.** Stiffener Web Thickness Data Statistical Analysis.

|  | Ratio Bias | Difference Bias (in.) |
|---|---|---|
| Mean | 1.25504 | 0.0503 |
| Standard Deviation | 0.11339 | 0.0180 |
| c.o.v. (%) | 9.035 | n/a |
| Standard Error | 0.007006 | 0.00111 |
| Median | 1.228571 | 0.04900 |
| Mode | 1.2058824 | 0.035 |
| Sample Variance | 0.012858 | 0.00033 |
| Kurtosis | 0.354754 | -0.38741 |
| Skewness | 0.899124 | 0.25728 |
| Range | 0.508110 | 0.088 |
| Minimum | 1.052174 | 0.012 |
| Maximum | 1.560284 | 0.1 |
| Count | 262 | 262 |
| Confidence Level (95.0%) | 0.013795 | 0.00219 |

### 4.6.2 *Stiffener Web Thickness Ratio Bias*

The web thickness ratio bias data were analyzed using a bin size of 11. The closeness of
the test statistics for the different p.d.f.'s makes a clear recommendation difficult. The
LogLogistic distribution is recommended as it is ranked first by the K-S and A-D tests, and the
Lognorm may be used should a simple model of the randomness be required. The Extreme
Value distribution appears to visually fit the best, as shown in Figure 4.6.2, but this is not
backed up by the ranking methods.

**TABLE 4.6.2.** Results from BestFit for Stiffener Web Thickness Ratio Bias.

| | Beta | Extreme Value Type I | Gamma | Inverse-Gaussian | Logistic | Log-Logistic | Lognorm | Triang |
|---|---|---|---|---|---|---|---|---|
| Param 1 | 7.6283 | 1.1977 | 169.8922 | 1.2388 | 1.2279 | 0.9385 | 1.2387 | 0.9074 |
| Param 2 | 15.3913 | 0.0805 | 0.0073 | 211.0422 | 0.0550 | 0.2721 | 0.0949 | 1.2156 |
| Param 3 | | | | | | 4.4047 | | 1.5243 |
| Adjust | +0.91 | | | | | | | |
| Mean | 1.2388 | 1.2442 | 1.2388 | 1.2388 | 1.2279 | 1.2351 | 1.2387 | 1.2158 |
| Mode | 1.2227 | 1.1977 | 1.2315 | 1.2279 | 1.2279 | 1.1835 | 1.2279 | 1.2156 |
| Median | 1.2338 | 1.2272 | 1.2363 | 1.2352 | 1.2279 | 1.2106 | 1.2351 | 1.2157 |
| Stnd Dev | 0.09604 | 0.10328 | 0.09504 | 0.09491 | 0.09969 | 0.13689 | 0.09491 | 0.17719 |
| Variance | 0.00922 | 0.01067 | 0.00903 | 0.00901 | 0.00994 | 0.01874 | 0.00901 | 0.03140 |
| Skewness | 0.28068 | 1.13955 | 0.15344 | 0.22984 | 0.00000 | 1.66107 | 0.23029 | 0.00089 |
| Kurtosis | 1.76317 | 5.40000 | 3.03532 | 3.08805 | 4.20000 | 7.62954 | 3.09443 | 2.38805 |
| C-S Test | 35.4 | 14818 | 31.0 | 28.6 | 40.3 | 38.0 | 28.6 | 61.1 |
| C-S Rank | | | 3 | 1 | | | 2 | |
| K-S Test | 0.1336 | 0.1131 | 0.1404 | 0.1390 | 0.1539 | 0.1093 | 0.1389 | 0.1196 |
| K-S Rank | | 2 | | | | 1 | | 3 |
| A-D Test | 42.962 | 340.061 | 54.460 | 57.835 | 32.554 | 24.859 | 56.994 | 54.429 |
| A-D Rank | 3 | | | | 2 | 1 | | 5 |
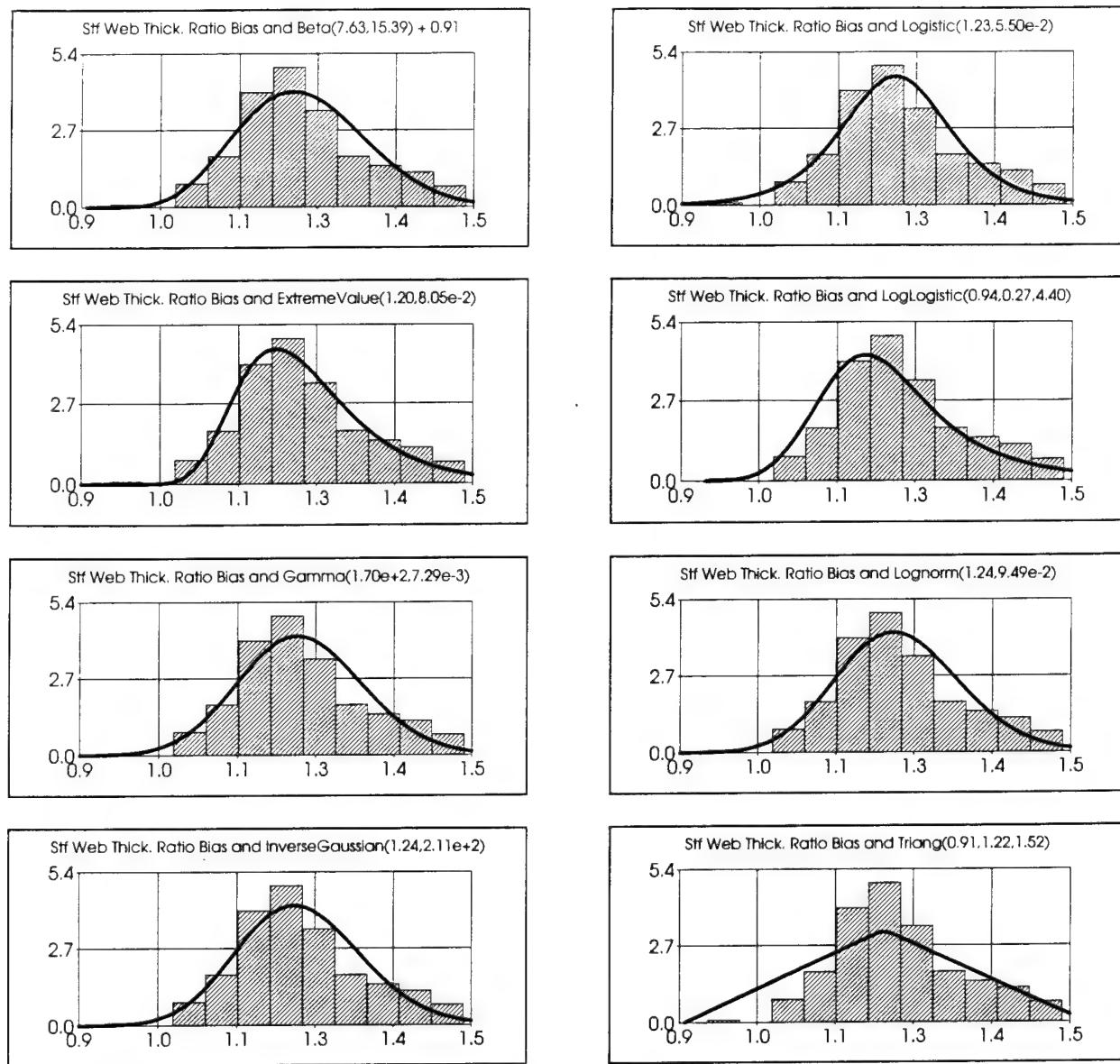
**FIGURE 4.6.2.** Stiffener Web Thickness Ratio Bias Distribution Fit with the Most Highly Ranked Probability Density Functions.

### 4.6.3  Stiffener Web Thickness Difference Bias

BestFit was used to analyze bin sizes 6 and 13, with good agreement. Results from the bin size of 13 are shown in Table 4.6.3 and Figure 4.6.3. The Weibull distribution is ranked highly by each method and is recommended for use. Should a simpler p.d.f. be needed, the Normal distribution would be an adequate representation of the web thickness difference bias, as the test statistics are relatively good and it matches quite well visually.

**TABLE 4.6.3.**  Results from BestFit for Stiffener Web Thickness Difference Bias (inches).

|  | Extreme Value Type I | Gamma | Logistic | Normal | Triang | Weibull |
|---|---|---|---|---|---|---|
| Param 1 | 0.04235 | 7.08806 | 0.04870 | 0.04849 | 8.24E-03 | 3.04681 |
| Param 2 | 0.01629 | 7.25E-03 | 0.01142 | 0.01884 | 0.04638 | 0.05637 |
| Param 3 |  |  |  |  | 0.10011 |  |
| Adjust |  |  |  |  |  |  |
| Mean | 0.05175 | 0.05140 | 0.04870 | 0.04849 | 0.05158 | 0.05038 |
| Mode | 0.04235 | 0.04415 | 0.04870 | 0.04849 | 0.04638 | 0.04947 |
| Median | 0.04832 | 0.04900 | 0.04870 | 0.04849 | 0.05043 | 0.04998 |
| Stnd Dev | 0.02089 | 0.01931 | 0.02071 | 0.01884 | 0.01930 | 0.01806 |
| Variance | 4.4E-04 | 3.7E-04 | 4.3E-04 | 3.6E-04 | 3.7E-04 | 3.3E-04 |
| **Skewness** | **1.1** | **0.75** | **0.0** | **0.0** | **0.16** | **0.14** |
| **Kurtosis** | **5.4** | **3.8** | **4.2** | **3.0** | **2.4** | **2.6** |
| C-S Test | 26.2091 | 21.3339 | 17.4397 | 18.2992 | 14.9406 | 16.0507 |
| C-S Rank |  |  | **3** |  | **1** | **2** |
| K-S Test | 0.05714 | 0.04434 | 0.05969 | 0.06524 | 0.07331 | 0.04277 |
| K-S Rank | **3** | **2** | **4** |  |  | **1** |
| A-D Test | 1.36647 | 0.90935 | 1.44330 | 1.51992 | 1.21188 | 0.57945 |
| A-D Rank | **4** | **2** | **5** |  | **3** | **1** |
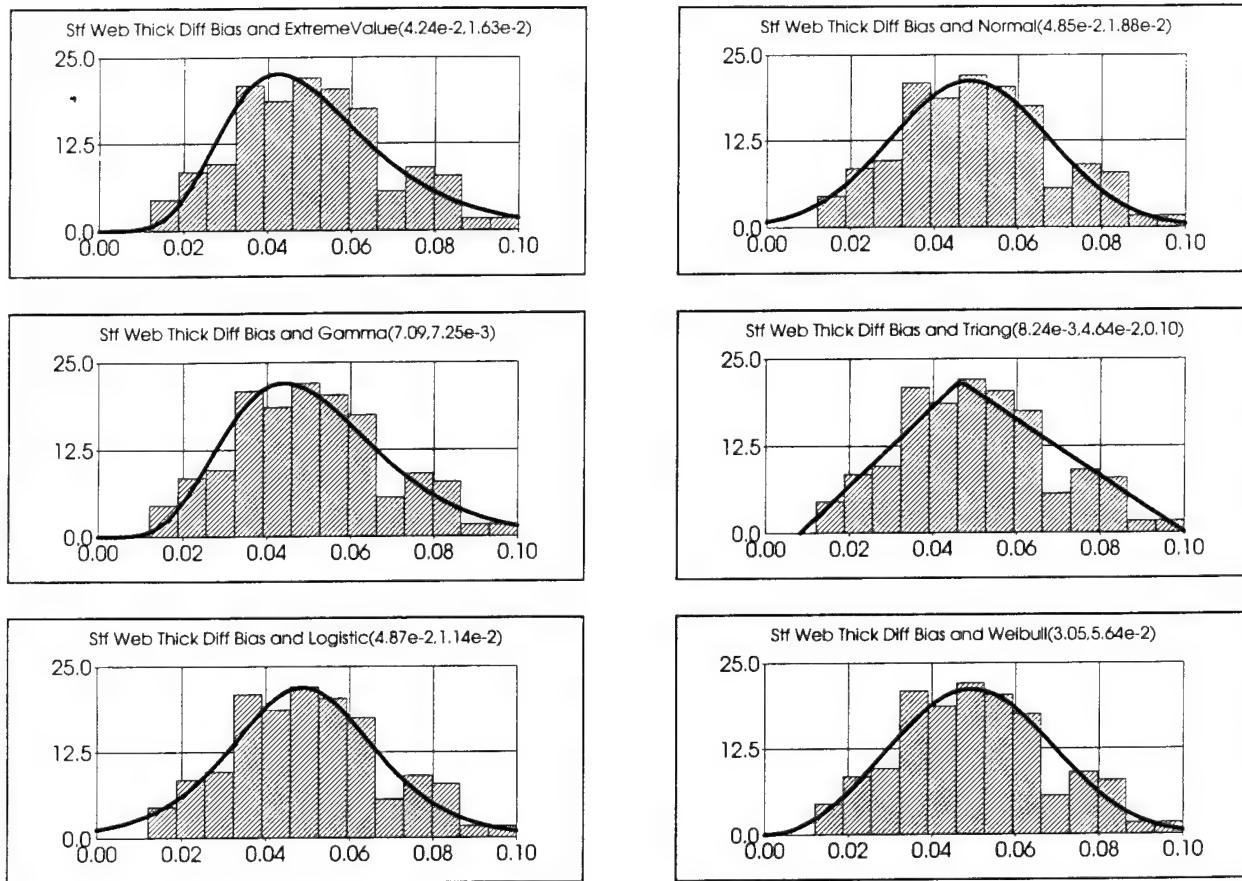
**FIGURE 4.6.3.** Stiffener Web Thickness Difference Bias (inches) Distribution Fit with the Most Highly Ranked Probability Density Functions.

## 4.7  Stiffener Flange Breadth

### 4.7.1  Stiffener Flange Breadth Data

Measurement of the stiffener flange breadth was done onboard current US Navy ships using a ruler and measuring to the nearest 32nd of an inch (0.03125).  The accuracy of the measurements generally lacks the resolution found in other measurements due to the magnitudes of the measured value relative to the level of precision.  The statistics of the data are presented in Table 4.7.1.

**TABLE 4.7.1.**  Stiffener Flange Breadth Data Statistical Analysis.

|  | Ratio Bias | Difference Bias (in.) |
|---|---|---|
| Mean | 1.01444 | 0.0587 |
| Standard Deviation | 0.01634 | 0.0649 |
| c.o.v. (%) | 1.611 | n/a |
| Standard Error | 0.000735 | 0.00292 |
| Median | 1.01389 | 0.05000 |
| Mode | 1.03109 | 0.1225 |
| Sample Variance | 0.000267 | 0.00422 |
| Kurtosis | -0.009167 | -0.20558 |
| Skewness | 0.212197 | 0.31857 |
| Range | 0.09500 | 0.3725 |
| Minimum | 0.967817 | -0.125 |
| Maximum | 1.062817 | 0.2475 |
| Count | 495 | 495 |
| Confidence Level (95.0%) | 0.001443 | 0.00573 |

### 4.7.2 Stiffener Flange Breadth Ratio Bias

The ratio bias data were grouped into bin sizes of 5 and 9. The results presented are for the bin size of 9, as the two bin size results are in close agreement. The recommended distribution is the Logistic as it is ranked highly by the C-S and A-D tests in Table 4.7.2, and visually fits the histogram quite well in Figure 4.7.2. The LogLogistic has a higher ranking by the K-S and A-D tests, but has a pronounced skewness to the left of the main body of data. For a simpler model, the Lognormal distribution is a valid second choice.

**TABLE 4.7.2.** Results from BestFit for Stiffener Flange Breadth Ratio Bias.

|  | Beta | Extreme Value Type I | Logistic | Log-Logistic | Lognorm | Weibull |
|---|---|---|---|---|---|---|
| Param 1 | 7.713452 | 1.007082 | 1.014438 | 0.967817 | 1.014438 | 69.10028 |
| Param 2 | 157.70 | 0.012744 | 0.00895 | 0.041314 | 0.01631 | 1.023791 |
| Param 3 |  |  |  | 3.734846 |  |  |
| Adjust | + 0.97 |  |  |  |  |  |
| Mean | 1.014438 | 1.014438 | 1.014438 | 1.014438 | 1.014438 | 1.015448 |
| Mode | 1.008889 | 1.007082 | 1.014438 | 1.003485 | 1.014045 | 1.023575 |
| Median | 1.012619 | 1.011753 | 1.014438 | 1.009131 | 1.014307 | 1.018375 |
| Stnd Dev | 0.016344 | 0.016344 | 0.016237 | 0.026757 | 0.016306 | 0.018653 |
| Variance | 2.67E-04 | 2.67E-04 | 2.64E-04 | 7.16E-04 | 2.66E-04 | 3.48E-04 |
| Skewness | 0.662746 | 1.139547 | 0 | 2.000414 | 0.048227 | -0.93525 |
| Kurtosis | -0.53856 | 5.4 | 4.2 | 9.368377 | 3.004135 | 4.135345 |
| C-S Test | 445.4091 | 5514.225 | 30.42647 | 137.7228 | 33.66104 | 162.0018 |
| C-S Rank |  |  | 1 |  | 2 |  |
| K-S Test | 0.123138 | 0.139002 | 0.146217 | 0.115527 | 0.146227 | 0.240176 |
| K-S Rank | 2 | 3 |  | 1 |  |  |
| A-D Test | 84.98341 | 1710.043 | 62.031 | 60.27126 | 121.0605 | 55.33896 |
| A-D Rank |  |  | 3 | 2 |  | 1 |
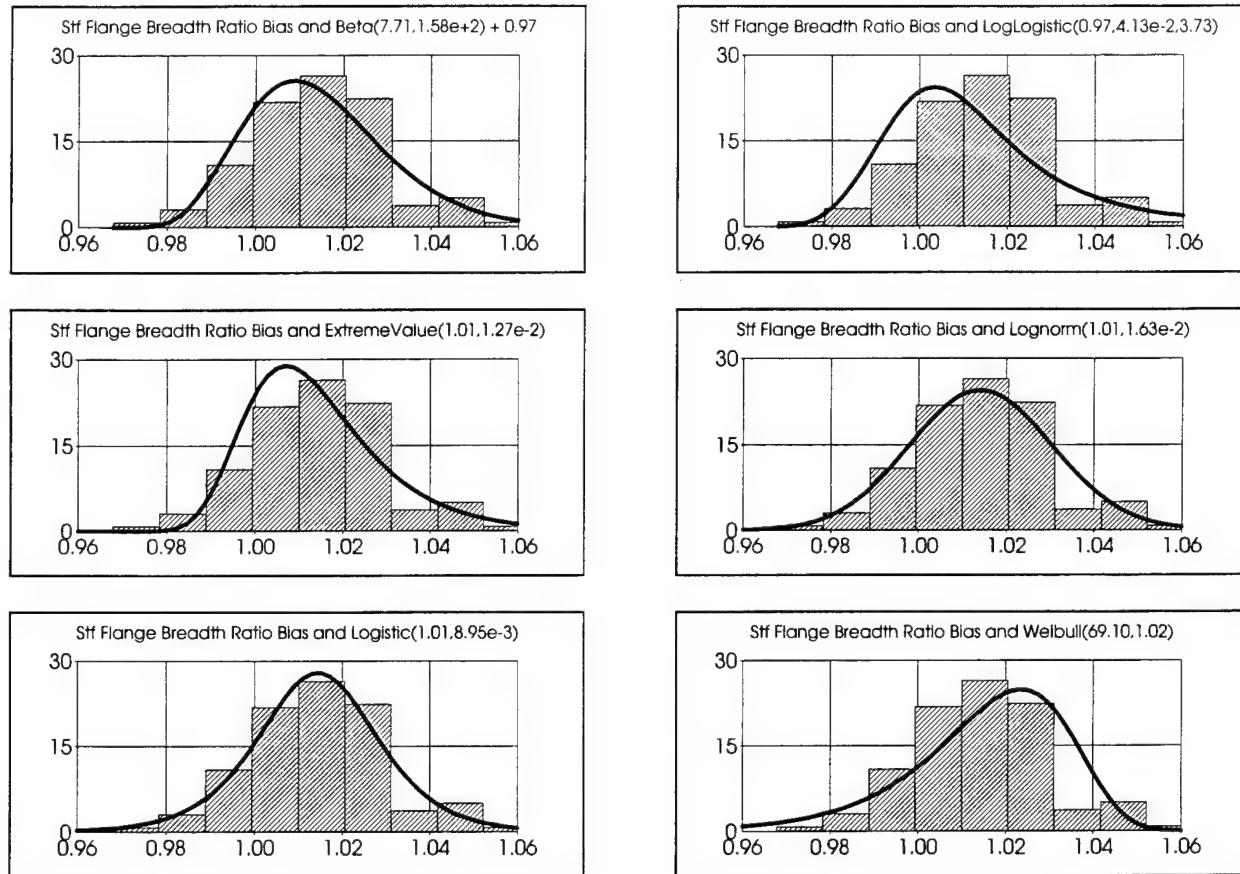
**FIGURE 4.7.2.** Stiffener Flange Breadth Ratio Bias Distribution Fit with the Most Highly Ranked Probability Density Functions.

*4.7.3 Stiffener Flange Breadth Difference Bias*

The difference bias was analyzed by BestFit using bin sizes of 5 and 6, with the results shown from the bin size of 5 classes. The Logistic distribution is recommended as the best model of the randomness of the flange breadth stiffener difference bias, as it visually matches quite well, and is ranked highly by both the C-S and A-D tests. The Normal distribution also has a very good fit, visually, is ranked highly by the C-S test, and is much simpler to use. The Weibull should not be used as it is truncated at the lower bound, inside of three standard deviations from the mean.

**TABLE 4.7.3.** Results from BestFit for Stiffener Flange Breadth Difference Bias (inches).

| | Inverse Gaussian | Logistic | Log-Logistic | Normal | Rayleigh | Weibull |
|---|---|---|---|---|---|---|
| Param 1 | 0.186814 | 0.056493 | -0.125 | 0.057327 | 0.139834 | 2.919893 |
| Param 2 | 0.690794 | 0.046588 | 0.162652 | 0.07441 | | 0.212387 |
| Param 3 | | | 3.724941 | | | |
| Adjust | -0.13 | | | | -0.13 | -0.13 |
| Mean | 0.058664 | 0.056493 | 0.058664 | 0.0573 | 0.047106 | 0.061287 |
| Mode | -2.33E-03 | 0.056493 | 0.015309 | 0.057327 | 1.17E-02 | 0.055828 |
| Median | 0.036752 | 0.056493 | 0.037652 | 0.057327 | 0.036492 | 0.059182 |
| Stnd Dev | 0.09715 | 0.084502 | 0.105803 | 0.07441 | 0.091611 | 0.070541 |
| Variance | 9.44E-03 | 7.14E-03 | 0.011194 | 5.54E-03 | 8.39E-03 | 4.98E-03 |
| Skewness | 1.560099 | 0 | 2.006486 | 0 | 0.631111 | 0.175543 |
| Kurtosis | 7.056514 | 4.2 | 9.401942 | 3 | 3.245089 | 2.640925 |
| C-S Test | 85.79154 | 11.27508 | 66.94176 | 8.651383 | 81.62573 | 3.113398 |
| C-S Rank | | 3 | | 2 | | 1 |
| K-S Test | 0.109014 | 0.140414 | 0.105968 | 0.144888 | 0.104251 | 0.154651 |
| K-S Rank | 3 | | 2 | | 1 | |
| A-D Test | 79.22083 | 41.82745 | 55.8065 | 105.4216 | 54.60688 | 63.26518 |
| A-D Rank | | 1 | 3 | | 2 | |
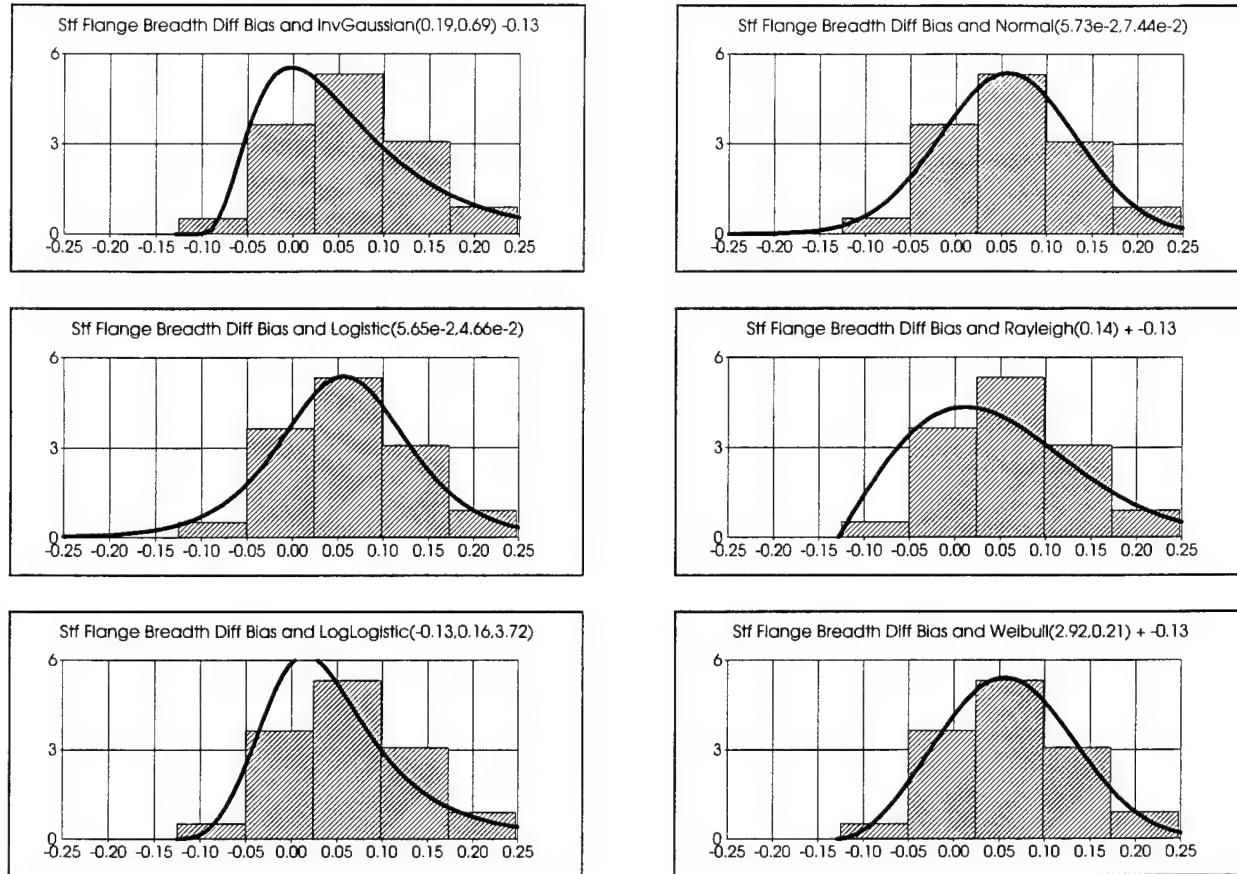
**FIGURE 4.7.3.** Stiffener Flange Breadth Difference Bias (inches) Distribution Fit with the Most Highly Ranked Probability Density Functions.

## 4.8 Stiffener Flange Thickness

### 4.8.1 Stiffener Flange Thickness Data

The stiffener flange thickness was measured with a micrometer. Factors influencing the measurement are the amount of paint on the flange, and the degree of taper of the flange, from the centerline to the edge. The measurements were meant to be taken at the mid-point between the centerline and the edge of the flange, giving an average thickness across the breadth. (Please look in Appendix C for further discussion.) The statistics of the biases are reported in Table 4.8.1.

**TABLE 4.8.1.** Stiffener Flange Thickness Data Statistical Analysis.

|  | Ratio Bias | Difference Bias (in.) |
|---|---|---|
| Mean | 1.13208 | 0.0293 |
| Standard Deviation | 0.10377 | 0.0212 |
| c.o.v. (%) | 9.167 | n/a |
| Standard Error | 0.004737 | 0.00097 |
| Median | 1.101587 | 0.02500 |
| Mode | 1.1 | 0.03 |
| Sample Variance | 0.010769 | 0.00045 |
| Kurtosis | 1.315159 | 0.83884 |
| Skewness | 1.236417 | 1.01177 |
| Range | 0.550000 | 0.11 |
| Minimum | 0.940000 | -0.012 |
| Maximum | 1.490000 | 0.098 |
| Count | 480 | 480 |
| Confidence Level (95.0%) | 0.009307 | 0.00190 |

## 4.8.2 Stiffener Flange Thickness Ratio Bias

The BestFit analysis was conducted using bin sizes of 10 and 14 with close agreement. The results from the analysis done using a bin size of 10 is shown below in Table 4.8.2 and Figure 4.8.2. The goodness-of-fit tests all rank the Extreme Value distribution as the best, and so it is recommended. The Beta distribution is truncated at the lower tail and may not be an appropriate second choice. The Lognormal would be suitable for simple applications.

**TABLE 4.8.2.** Results from BestFit for Stiffener Flange Thickness Ratio Bias.

|          | Beta     | Extreme Value Type I | Logistic | Lognorm  | PearsonV | Triang   |
|----------|----------|----------------------|----------|----------|----------|----------|
| Param 1  | 2.580576 | 1.085381             | 1.109394 | 1.131955 | 134.6724 | 0.939811 |
| Param 2  | 10.84085 | 0.080912             | 0.05849  | 0.099231 | 151.2973 | 1.052698 |
| Param 3  |          |                      |          |          |          | 1.490189 |
| Adjust   | +0.94    |                      |          |          |          |          |
| Mean     | 1.132084 | 1.132084             | 1.109394 | 1.131955 | 1.131851 | 1.160899 |
| Mode     | 1.078198 | 1.085381             | 1.109394 | 1.119031 | 1.115166 | 1.052698 |
| Median   | 1.116577 | 1.115036             | 1.109394 | 1.127631 | 1.126233 | 1.143212 |
| Stnd Dev | 0.103774 | 0.103774             | 0.106088 | 0.099231 | 0.098265 | 0.141347 |
| Variance | 0.010769 | 0.010769             | 0.011255 | 0.009847 | 0.009656 | 0.019979 |
| Skewness | 0.769155 | 1.139547             | 0        | 0.263665 | 0.316829 | 0.468865 |
| Kurtosis | 4.017405 | 5.4                  | 4.2      | 3.123847 | 2.989025 | 2.387457 |
| C-S Test | 54.29496 | 32.32573             | 124.5596 | 134.79   | 118.0758 | 92.45097 |
| C-S Rank | 2        | 1                    |          |          |          | 3        |
| K-S Test | 0.074839 | 0.066934             | 0.111824 | 0.11745  | 0.113    | 0.180975 |
| K-S Rank | 2        | 1                    | 3        |          |          |          |
| A-D Test | 5.616364 | 2.948839             | 12.23085 | 11.006   | 9.796389 | 22.04707 |
| A-D Rank | 2        | 1                    |          |          | 3        |          |
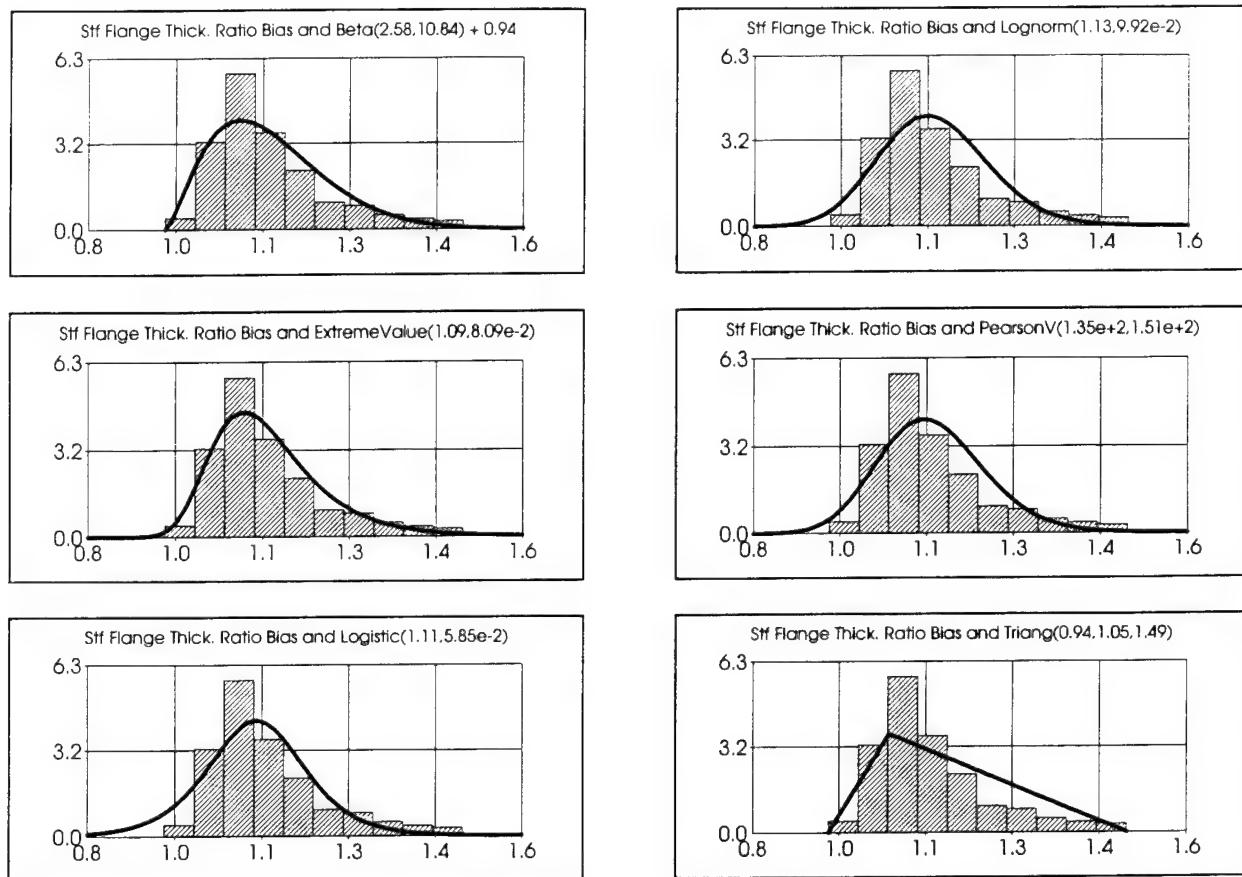
**FIGURE 4.8.2.** Stiffener Flange Thickness Ratio Bias Distribution Fit with the Most Highly Ranked Probability Density Functions.

*4.8.3 Stiffener Flange Thickness Difference Bias*

The results shown in Table 4.8.3 and Figure 4.8.3 are for a bin of 10; only this bin was used for the analysis. The goodness-of-fit tests all agree on the Extreme Value distribution as the best match for the flange thickness difference bias, and visually it matches as well. The Beta distribution is again ranked as a second choice, but is truncated, as is the Gamma. A simpler model may be found in the Lognormal distribution.

**TABLE 4.8.3.** Results from BestFit for Stiffener Flange Thickness Difference Bias (inches).

|  | Beta | Extreme Value Type I | Gamma | Lognorm |
|---|---|---|---|---|
| Param 1 | 3.600181 | 0.019737 | 3.237298 | 0.050661 |
| Param 2 | 83.54 | 0.016528 | 0.012653 | 0.040166 |
| Param 3 |  |  |  |  |
| Adjust | -0.012 |  | -0.012 | -0.012 |
| Mean | 0.029277 | 0.029277 | 0.028923 | 0.038624 |
| Mode | 0.018502 | 0.019737 | 0.01627 | 0.012338 |
| Median | 0.025809 | 0.025795 | 0.024792 | 0.027661 |
| Stnd Dev | 0.021198 | 0.021198 | 0.022766 | 0.040166 |
| Variance | 4.49E-04 | 4.49E-04 | 5.18E-04 | 1.61E-03 |
| Skewness | 0.970951 | 1.139547 | 1.111575 | 2.876851 |
| Kurtosis | 3.867678 | 5.4 | 4.853397 | 20.63028 |
| C-S Test | 23.94209 | 20.49686 | 23.3588 | 39.7964 |
| C-S Rank | 3 | 1 | 2 |  |
| K-S Test | 0.063129 | 0.055934 | 0.070673 | 0.122803 |
| K-S Rank | 2 | 1 | 3 |  |
| A-D Test | 2.104283 | 1.184184 | 3.575115 | 14.6967 |
| A-D Rank | 2 | 1 | 3 |  |
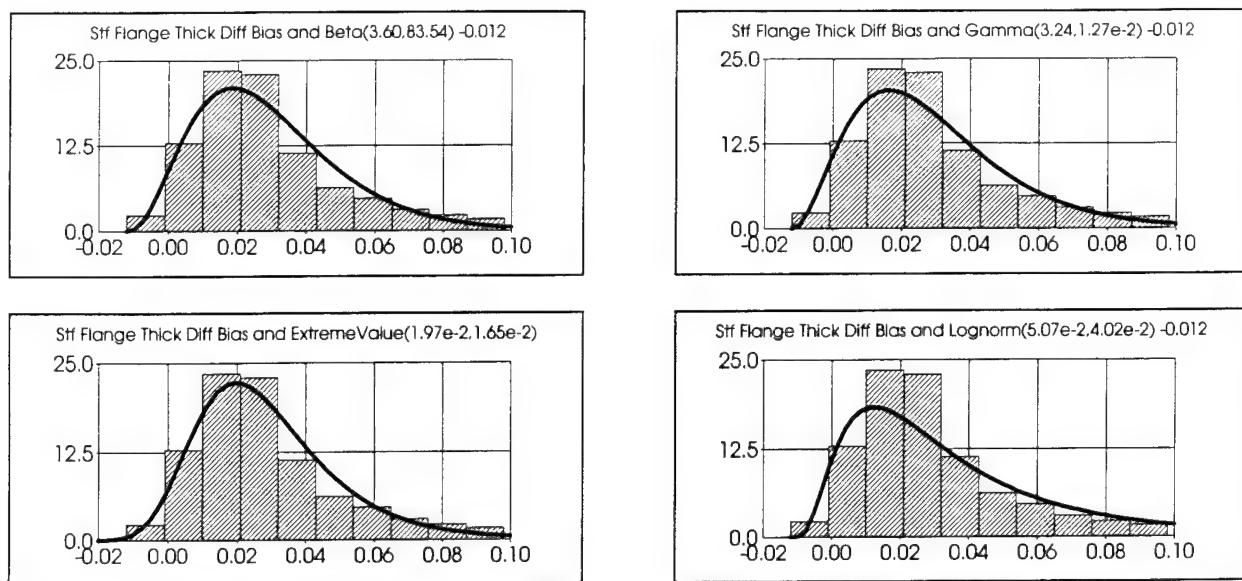
**FIGURE 4.8.3.** Stiffener Flange Thickness Difference Bias (inches) Distribution Fit with the Most Highly Ranked Probability Density Functions.

# 5.0 DISTORTIONS

## 5.1 Unstiffened Plate Distortion

### *5.1.1 Unstiffened Plate Distortion Uncertainty Literature Survey*

Two studies were found in the literature of distortion levels in unstiffened plating due to construction: Antinou (1980) and Kmiecik et al (1995). Antinou (1980) considered the central plate deflection as a function of basic variables such as geometry and welding techniques, and new formulations for prediction based on these variables are presented. The maximum deflection of 2052 plates from newly built ships were measured with the distribution of data from 774 samples shown in histograms. The reported statistics are reported as shown in Table 5.1.1, normalized by the thickness and the breadth of the plate.

**TABLE 5.1.1a.** Maximum Plating Distortion from Antinou (1980).

|  | Normalized by Plate Breadth | Normalized by Plate Thickness |
|---|---|---|
| Mean | 0.0037973 | 0.204959 |
| Standard Deviation | 0.0015181 | 0.082229 |

Kmiecik et al (1995) conducted a survey of ship plating from newly built ships (post-fabrication) with measurements made of 1998 plates over a period of 15 years. The ships were built in Polish and German shipyards. The maximum deflection of the plates were investigated as well as the deflection geometry. The plate distortions were normalized to the plate thickness. The normalized data were grouped by panel aspect ratio (a/b) and slenderness (b/t), the histograms and statistics for each were presented, and Weibull distribution variables were calculated. Summaries of the statistics are presented in Table 5.1.1b and 5.1.1c.

**TABLE 5.1.1b.** Maximum Plating Distortion vs. Aspect Ratio (a/b) from Kmiecik et al (1995).

| Aspect Ratio (a/b) Range | Mean (dist / thickness) | Standard Deviation (dist / thickness) | Number of Samples |
|---|---|---|---|
| 1.00-1.41 | 0.156 | 0.183 | 538 |
| 1.41-2.45 | 0.356 | 0.369 | 754 |
| 2.45-3.46 | 0.291 | 0.384 | 589 |
| Total Sample Population | 0.278 | 0.342 | 1881 |

Note: total sample statistics were derived by the authors.

**TABLE 5.1.1c.** Maximum Plating Distortion vs. slenderness (b/t) from Kmiecik et al (1995).

| Slenderness (b/t) Range | Mean (dist / thickness) | Standard Deviation (dist / thickness) | Number of Samples |
|---|---|---|---|
| 25-35 | 0.117 | 0.088 | 302 |
| 35-45 | 0.176 | 0.153 | 707 |
| 45-55 | 0.149 | 0.154 | 277 |
| 55-65 | 0.223 | 0.166 | 254 |
| 65-75 | 0.337 | 0.372 | 155 |
| 75-85 | 0.553 | 0.34 | 38 |
| Total Sample Population | 0.191 | 0.199 | 1733 |

Note: total sample statistics were derived by the authors.

## 5.1.2 Unstiffened Plate Distortion Data

The NSWC on-board measurements were collected by measuring the distortion in three locations on the unstiffened plate: the middle and near the two ends. For each measurement location, two points were measured near the edges of the panel. Due to the flange of the stiffener obstructing a measurement near the edge weld, each of these measurements is offset from the edge by one half of the stiffener flange breadth. As distortion is initiated at the weld, the use of a baseline point on the plate away from the weld, may cause the final calculated distortion to be less than actual. The mode shape of the distortion was not observed either, and so the analysis focuses on the maximum of these three measurements for each plate. The maximum distortion is normalized in two ways: the first uses the measured breadth of the plate (short dimension or stiffener spacing), and the second uses the (nominal) plate thickness.

**TABLE 5.1.2.** Unstiffened Plate Distortion Bias Statistical Analysis.

|  | Distortion/Breadth Ratio | Distortion/Thickness Ratio |
|---|---|---|
| Mean | 0.010821 | 0.786791 |
| Standard Deviation | 0.010634 | 0.921504 |
| c.o.v. (%) | 98.278 | n/a |
| Standard Error | 0.000673 | 0.109362 |
| Median | 0.006694 | 0.5000 |
| Mode | 0.028 | 0.5 |
| Sample Variance | 0.000113 | 0.849170 |
| Kurtosis | 1.239366 | 7.690008 |
| Skewness | 1.456722 | 2.488630 |
| Range | 0.043767 | 5.008013 |
| Minimum | 0.0 | 0.0 |
| Maximum | 0.043767 | 5.008013 |
| Count | 250 | 71 |
| Confidence Level (95.0%) | 0.001325 | 0.218116 |

*5.1.3 Unstiffened Plate Distortion Bias as Normalized to the Plate Breadth*

The plate distortion data were analyzed using 7 bins, and was normalized to the nominal plate breadth. The goodness-of-fit tests lead to four distributions, with most agreement on the Exponential distribution. The A-D test ranks the Log-Logistic distribution highest, but the second choice of the Exponential distribution may be a better choice as it's mean and standard deviation most closely resemble the raw data.

**TABLE 5.1.3.** Results from BestFit for Unstiffened Plate Distortion Bias (Normalized to Nominal Plate Breadth).

|  | Beta | Exponential | LogLogistic | Lognormal |
|---|---|---|---|---|
| Param 1 | 1.014151 | 0.010825 | -1.505E-3 | 0.0166 |
| Param 2 | 92.66994 |  | 8.702E-3 | 0.025181 |
| Param 3 |  |  | 1.831404 |  |
| Adjust | -4.39E-06 | -4.39E-06 |  | -4.39E-06 |
| Mean | 0.010821 | 0.010821 | 0.01358 | 0.016596 |
| Mode | 1.50E-04 | -4.39E-06 | 2.952E-3 | 2.764E-3 |
| Median | 7.594E-3 | 7.499E-3 | 7.197E-3 | 9.132E-3 |
| Stnd Dev | 0.010634 | 0.010825 | 0.019611 | 0.025181 |
| Variance | 1.13E-04 | 1.17E-04 | 3.85E-04 | 6.34E-04 |
| Skewness | 1.922949 | 2.0 | 4.600733 | 8.040982 |
| Kurtosis | 10.37114 | 9.0 | 30.2749 | 220.356 |
| C-S Test | 20.23298 | 19.31806 | 19.58214 | 7.388209 |
| C-S Rank |  | 2 | 3 | 1 |
| K-S Test | 0.071753 | 0.068747 | 0.062444 | 0.139021 |
| K-S Rank | 3 | 2 | 1 |  |
| A-D Test | 1.829745 | 1.822983 | 1.586659 | 9.961655 |
| A-D Rank | 3 | 2 | 1 |  |
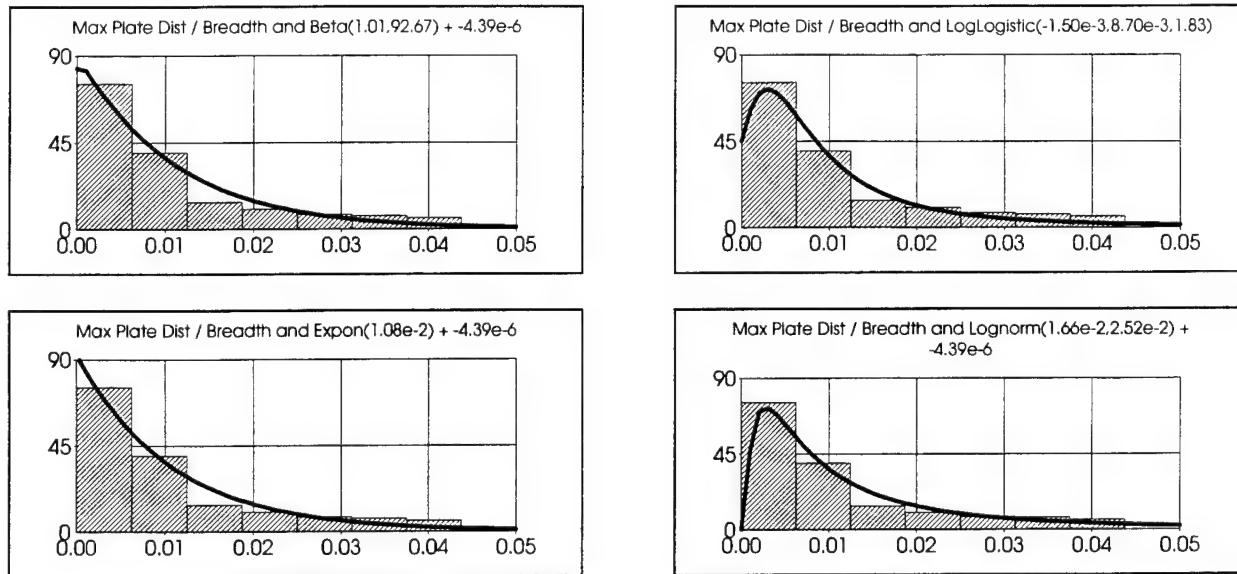
**FIGURE 5.1.3.** Unstiffened Plate Distortion Bias (Normalized to Plate Breadth) Distribution Fit with the Most Highly Ranked Probability Density Functions.

*5.1.4  Unstiffened Plate Distortion Bias as Normalized to the Plate Thickness*

The plate distortion data were analyzed using 7 bins, and normalized to the nominal plate thickness.  The top ranked distribution by the K-S and A-D goodness-of-fit methods is the Weibull,  with the A-D showing a preference to the Pearson IV.  As the Weibull is closely ranked and looks better visually,  it seems the better choice.  A simpler model may be found using the Exponential distribution.

**TABLE 5.1.4.**  Results from BestFit for Unstiffened Plate Distortion Bias (Normalized to Plate Thickness).

|          | Exponential | Gamma     | LogLogistic | Lognormal | Pearson VI | Weibull   |
|----------|-------------|-----------|-------------|-----------|------------|-----------|
| Param 1  | 0.787144    | 0.729648  | -0.15271    | 1.088279  | 1.34       | 0.911648  |
| Param 2  |             | 1.078799  | 0.585219    | 2.707009  | 2.70       | 0.751915  |
| Param 3  |             |           | 1.726962    |           | 1.078799   |           |
| Adjust   | -3.53E-04   | -3.53E-04 |             | -3.53E-04 | -3.53E-04  | -3.53E-04 |
| Mean     | 0.786791    | 0.786791  | 0.945586    | 1.087926  | 0.847      | 0.78534   |
| Mode     | -3.525E-4   | -3.524E-4 | 0.119466    | 0.056127  | 0.098056   | -3.525E-4 |
| Median   | 0.545254    | 0.469014  | 0.432512    | 0.405584  | 0.464461   | 0.502647  |
| Stnd Dev | 0.787144    | 0.921504  | 1.542994    | 2.707009  | 1.523461   | 0.862975  |
| Variance | 0.619595    | 0.849170  | 2.380829    | 7.327899  | 2.320935   | 0.744725  |
| Skewness | 2           | 2.341387  | 4.910304    | 22.85262  | 3.658038   | 1.981412  |
| Kurtosis | 9           | 11.22314  | 33.49508    | 3562.943  | 20.64427   | 7.751655  |
| C-S Test | 7.878024    | 6.003769  | 2.584853    | 2.424683  | 1.948481   | 5.282144  |
| C-S Rank |             |           | 3           | 2         | 1          |           |
| K-S Test | 0.114371    | 0.115372  | 0.144204    | 0.156426  | 0.122989   | 0.095556  |
| K-S Rank | 2           | 3         |             |           |            | 1         |
| A-D Test | 1.075263    | 1.132626  | 1.489745    | 1.138727  | 0.710527   | 0.796771  |
| A-D Rank | 3           |           |             |           | 1          | 2         |
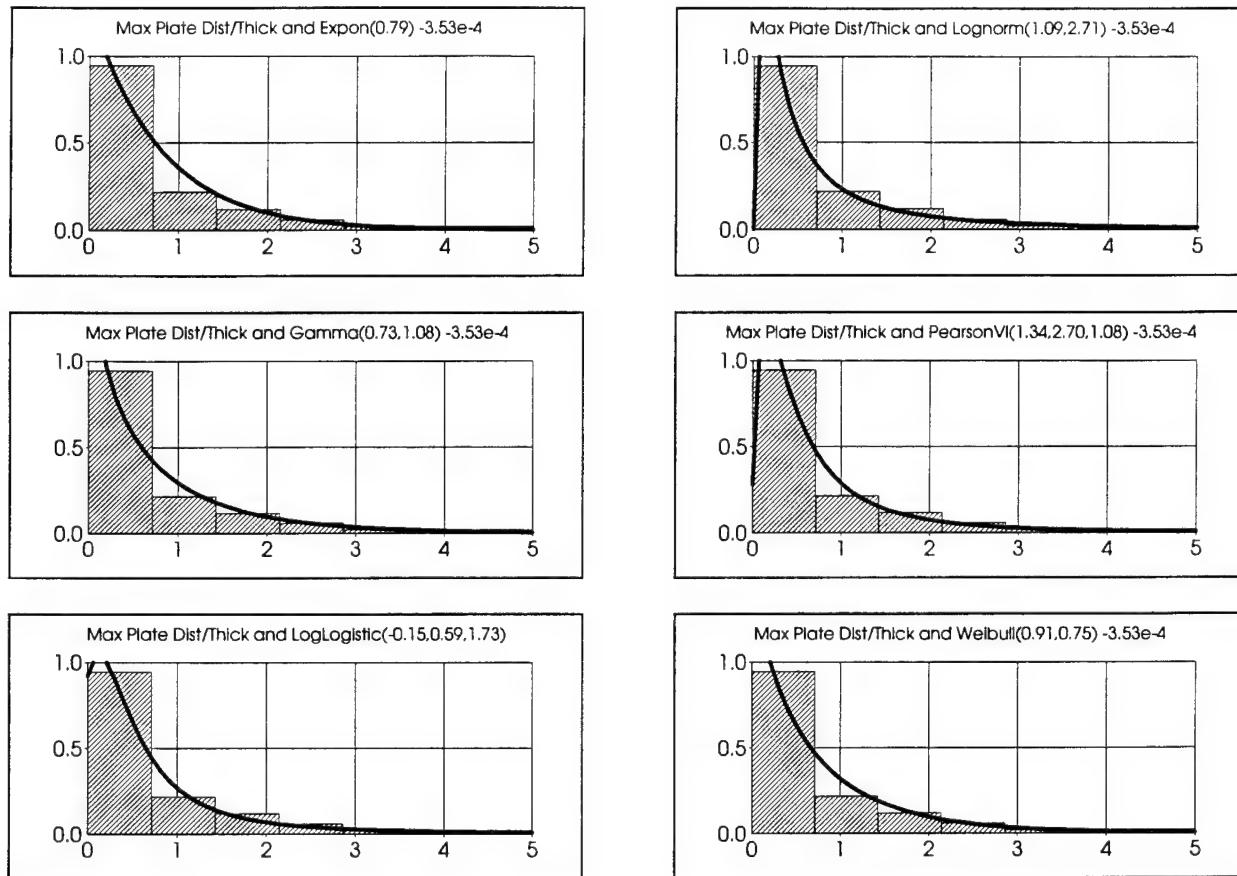
**FIGURE 5.1.4.** Unstiffened Plate Distortion Bias (Normalized to Plate Thickness) Distribution Fit with the Most Highly Ranked Probability Density Functions.

## 5.2  Stiffener Weak Axis Distortion

### 5.2.1  Stiffener Weak Axis Distortion Data

The stiffener weak axis (tripping) distortion is normalized to the measured stiffener length.  As weak axis distortion is considered one failure mode regardless of the direction,  the absolute values of the data were taken.  The data used for this analysis come from the survey of US Navy ships and the 4-point bending model.

**TABLE 5.2.1.** Stiffener Weak Axis Distortion Bias Statistical Analysis.

|  | Distortion/Length Ratio |
|---|---|
| Mean | 8.0653E-04 |
| Standard Deviation | 8.1621E-04 |
| c.o.v.  (%) | 101.2 |
| Standard Error | 5.2577E-05 |
| Median | 6.1576E-04 |
| Mode | 0 |
| Sample Variance | 6.6620E-07 |
| Kurtosis | 1.687204 |
| Skewness | 1.359000 |
| Range | 3.8226E-03 |
| Minimum | 0.0 |
| Maximum | 3.8226E-03 |
| Count | 241 |
| Confidence Level (95.0%) | 1.0357E-04 |

## 5.2.2 *Stiffener Weak Axis Distortion Bias as Normalized to the Stiffener Length*

The stiffener weak axis distortion data were divided into 12 classes for the analysis. The A-D test and its focus on the tails, would suggest that the Extreme Value Type I and possibly the Log-Logistic distributions are the best choices for reliability analyses and simulations. From visual inspection and a comparison of the mean and standard deviation to the raw data, the Exponential distribution may be appropriate in most cases.

**TABLE 5.2.2.** Results from BestFit for Stiffener Weak Axis Distortion Bias (Normalized to the Measured Stiffener Length).

| | Beta | Erlang | Exponential | Extreme Value Type I | LogLogistic | Normal | Weibull |
|---|---|---|---|---|---|---|---|
| Param 1 | 0.959637 | 1 | 8.19E-04 | 3.75E-04 | -1.45E-04 | 8.07E-04 | 0.960634 |
| Param 2 | 1132.823 | 8.66E-04 | | 5.98E-04 | 6.40E-04 | 8.16E-04 | 8.95E-04 |
| Param 3 | | | | | 1.693367 | | |
| Adjust | -1.27e-5 | -1.27e-5 | -1.27e-5 | | | | -1.27e-5 |
| Mean | 8.34E-04 | 8.53E-04 | 8.07E-04 | 7.20E-04 | 1.09E-03 | 8.07E-04 | 8.98E-04 |
| Mode | -1.27E-05 | -1.27E-05 | -1.27E-05 | 3.75E-04 | 1.43E-04 | 8.07E-04 | -1.27E-05 |
| Median | 5.65E-04 | 5.88E-04 | 5.55E-04 | 5.94E-04 | 4.95E-04 | 8.07E-04 | 5.98E-04 |
| Stnd Dev | 8.63E-04 | 8.66E-04 | 8.19E-04 | 7.67E-04 | 1.78E-03 | 8.16E-04 | 9.48E-04 |
| Variance | 7.45E-07 | 7.50E-07 | 6.71E-07 | 5.88E-07 | 3.18E-06 | 6.66E-07 | 8.99E-07 |
| Skewness | 2.036342 | 2 | 2 | 1.139547 | 5.016379 | 0 | 1.853226 |
| Kurtosis | 11.24609 | 9 | 9 | 5.4 | 34.62857 | 3 | 7.108256 |
| C-S Test | 9.640338 | 9.294415 | 11.43152 | 49.80426 | 17.26659 | 226.9775 | 8.266626 |
| C-S Rank | **3** | **2** | **5** | | | | **1** |
| K-S Test | 0.206832 | 0.209509 | 0.208685 | 0.153832 | 0.14945 | 0.170519 | 0.207424 |
| K-S Rank | | | | **2** | **1** | **3** | |
| A-D Test | 16.07605 | 17.87816 | 17.40581 | 4.62214 | 5.577797 | 9.794163 | 16.6818 |
| A-D Rank | | | | **1** | **2** | **3** | |
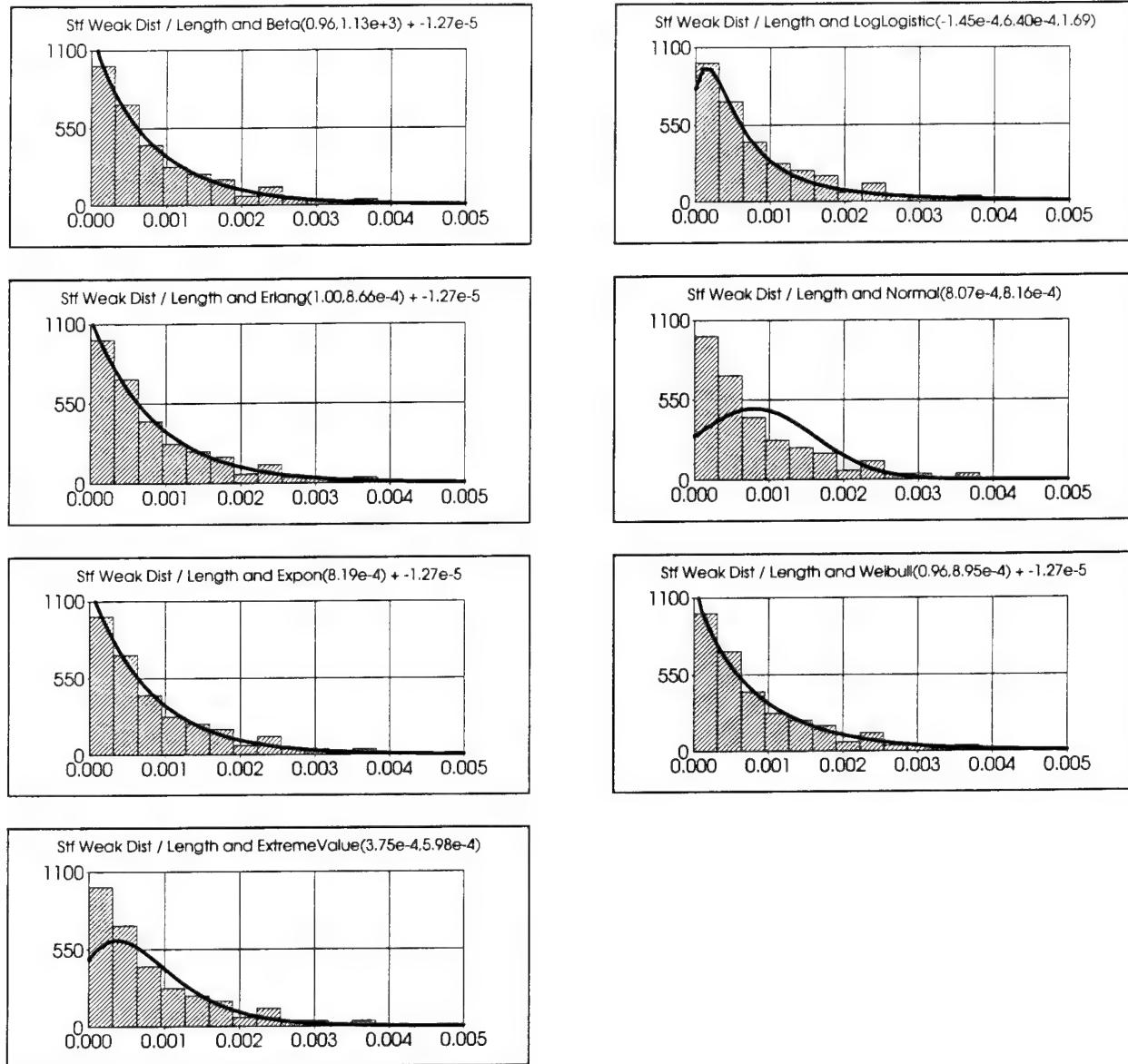
**FIGURE 5.2.2.** Stiffener Weak Axis Distortion Bias (Normalized to the Measured Stiffener Length) Distribution Fit with the Most Highly Ranked Probability Density Functions.

## 5.3 Stiffener Strong Axis Distortion

### *5.3.1 Stiffener Strong Axis Distortion Data*

The distortion of the stiffener about its strong axis may occur in two distinct directions which may be referred to as Mode I and II. Mode I distortion is similar to buckling failure where the stiffener flange is in compression. Mode II is where the plate flange is in compression. The amount of distortion has been normalized to the measured stiffener length. The data were gathered in one set and divided into the Mode I and II categories based on the whether its value was positive (Mode I) or negative (Mode II). The data points with zero distortion were combined with both subsets.

**TABLE 5.3.1.** Stiffener Strong Axis Data Statistical Analysis.

|  | Mode I | Mode II |
|---|---|---|
| Mean | 3.6453E-04 | 8.1615E-04 |
| Standard Deviation | 4.3743E-04 | 8.7497E-04 |
| c.o.v. (%) | 119.997 | 107.207 |
| Standard Error | 4.611E-05 | 7.292E-05 |
| Median | 2.501E-04 | 6.463E-04 |
| Mode | 0 | 0 |
| Sample Variance | 1.9134E-07 | 7.6558E-07 |
| Kurtosis | -0.138676 | 2.741640 |
| Skewness | 0.982995 | 1.527816 |
| Range | 1.4641E-03 | 4.2662E-03 |
| Minimum | 0.0 | 0.0 |
| Maximum | 1.4641E-03 | 4.2662E-03 |
| Count | 90 | 144 |
| Confidence Level (95.0%) | 9.1617E-07 | 1.4413E-04 |

*5.3.2 Stiffener Strong Axis (Mode I) Distortion Bias as Normalized to the Stiffener Length*

The data for stiffener strong axis distortion in Mode I (stiffener induced buckling) were divided into 8 bins for the analysis. The most highly ranked p.d.f., according to the K-S and A-D goodness-of-fit tests, is the Extreme Value Type I distribution. The Extreme Value Type I distribution is recommended for use in reliability analysis or simulation, where the emphasis is on the curve fit in the tails, due to its high ranking by the A-D test. The data visibly follows a curve very similar to what most would consider an Exponential distribution. The Exponential distribution may be considered for use in simplified applications.

**TABLE 5.3.2.** Results from BestFit for Stiffener Strong Axis (Mode I) Distortion Bias (Normalized to Measured Stiffener Length).

| | Beta | Erlang | Exponential | Extreme Value Type I | Gamma | Logistic | Log-Logistic | Normal | Weibull |
|---|---|---|---|---|---|---|---|---|---|
| Param 1 | 0.546946 | 1 | 4.47E-04 | 1.76E-04 | 0.551217 | 4.39E-04 | -1.41E-04 | 4.39E-04 | 0.903401 |
| Param 2 | 1173.326 | 5.33E-04 | | 4.41E-04 | 8.11E-04 | 3.30E-04 | 2.98E-04 | 6.02E-04 | 3.84E-04 |
| Param 3 | | | | | | | 1.481324 | | |
| Adjust | -7.61E-06 | -7.61E-06 | -7.61E-06 | | -7.61E-06 | | | | -7.61E-06 |
| Mean | 4.58E-04 | 5.25E-04 | 4.39E-04 | 4.30E-04 | 4.39E-04 | 4.39E-04 | 5.99E-04 | 4.39E-04 | 3.96E-04 |
| Mode | -7.61E-06 | -7.61E-06 | -7.61E-06 | 1.76E-04 | -7.61E-06 | 4.39E-04 | -4.27E-05 | 4.39E-04 | -7.61E-06 |
| Median | 2.21E-04 | 3.62E-04 | 3.02E-04 | 3.37E-04 | 2.13E-04 | 4.39E-04 | 1.57E-04 | 4.39E-04 | 2.48E-04 |
| Stnd Dev | 6.30E-04 | 5.33E-04 | 4.47E-04 | 5.65E-04 | 6.02E-04 | 5.98E-04 | 1.25E-03 | 6.02E-04 | 4.47E-04 |
| Variance | 3.96E-07 | 2.84E-07 | 2.00E-07 | 3.19E-07 | 3.63E-07 | 3.58E-07 | 1.55E-06 | 3.63E-07 | 2.00E-07 |
| Skewness | 2.69898 | 2 | 2 | 1.139547 | 2.693821 | 0 | 5.762759 | 0 | 2.004369 |
| Kurtosis | 16.36197 | 9 | 9 | 5.4 | 13.885 | 4.2 | 43.01322 | 3 | 7.871046 |
| C-S Test | 12.99535 | 8.253606 | 18.22066 | 28.76733 | 13.07099 | 71.78021 | 22.25297 | 930.0181 | 17.72643 |
| C-S Rank | 2 | 1 | 5 | | 3 | | | | 4 |
| K-S Test | 0.372548 | 0.443282 | 0.440579 | 0.232234 | 0.37197 | 0.248691 | 0.248682 | 0.232753 | 0.428941 |
| K-S Rank | | | | 1 | | 4 | 3 | 2 | |
| A-D Test | 13.44432 | 43.90387 | 40.91123 | 5.283776 | 13.53921 | 6.762834 | 6.880876 | 7.231513 | 32.03928 |
| A-D Rank | | | | 1 | | 2 | 3 | 4 | |
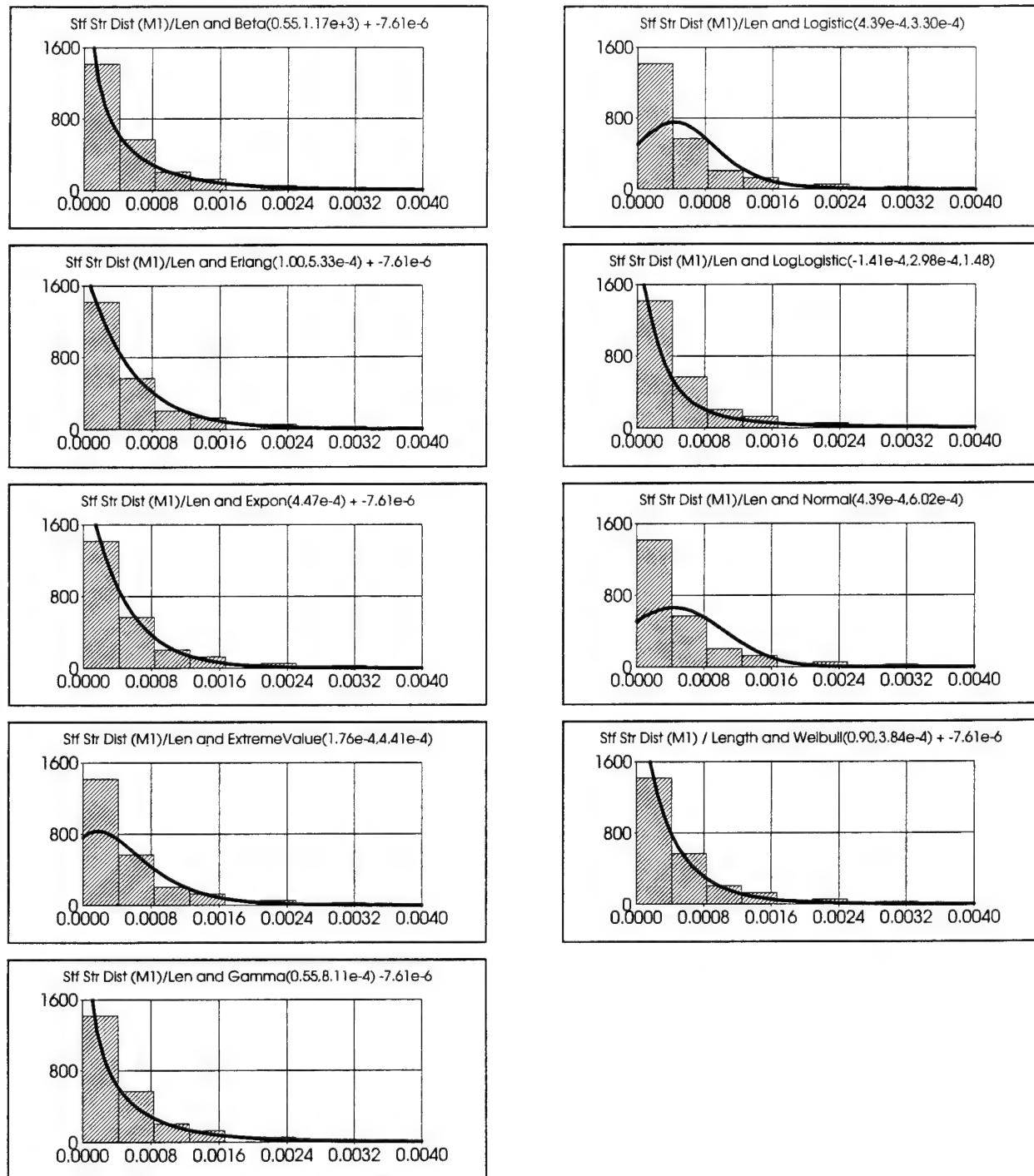
**FIGURE 5.3.2.** Stiffener Strong Axis (Mode I) Distortion Bias (Normalized to Measured Stiffener Length) Distribution Fit with the Most Highly Ranked Probability Density Functions.

*5.3.3 Stiffener Strong Axis Distortion (Mode II) Bias as Normalized to the Stiffener Length*

The data for stiffener strong axis distortion in Mode II (plating induced buckling) have been divided into 7 bins for the analysis. As with Mode I, the highest ranking was given to the Extreme Value Type I distribution by the K-S and A-D goodness-of-fit tests. As the A-D test is most interested in the fit near the tail, the Extreme Value Type I distribution would be good for simulation where the tails play an important role. For simplistic uses, the Exponential distribution may prove to be adequate.

**TABLE 5.3.3.** Results from BestFit for Stiffener Strong Axis (Mode II) Distortion Bias (Normalized to Measured Stiffener Length).

| | Erlang | Exponential | Extreme Value Type I | Logistic | Normal | Weibull |
|---|---|---|---|---|---|---|
| Param 1 | 1 | 9.82E-04 | 4.14E-04 | 7.75E-04 | 8.16E-04 | 1.115562 |
| Param 2 | 9.63E-04 | | 6.55E-04 | 4.73E-04 | 8.75E-04 | 1.01E-03 |
| Param 3 | | | | | | |
| Adjust | -5.83E-06 | -5.83E-06 | | | | -5.83E-06 |
| Mean | 9.57E-04 | 9.76E-04 | 7.92E-04 | 7.75E-04 | 8.16E-04 | 9.65E-04 |
| Mode | -5.83E-06 | -5.83E-06 | 4.14E-04 | 7.75E-04 | 8.16E-04 | 1.27E-04 |
| Median | 6.62E-04 | 6.75E-04 | 6.54E-04 | 7.75E-04 | 8.16E-04 | 7.22E-04 |
| Stnd Dev | 9.63E-04 | 9.82E-04 | 8.40E-04 | 8.57E-04 | 8.75E-04 | 8.72E-04 |
| Variance | 9.28E-07 | 9.64E-07 | 7.05E-07 | 7.35E-07 | 7.66E-07 | 7.60E-07 |
| Skewness | 2 | 2 | 1.139547 | 0 | 0 | 1.521839 |
| Kurtosis | 9 | 9 | 5.4 | 4.2 | 3 | 5.632021 |
| C-S Test | 3.52758 | 3.572351 | 10.90458 | 43.89406 | 101.9498 | 2.713697 |
| C-S Rank | **2** | **3** | | | | **1** |
| K-S Test | 0.292576 | 0.292688 | 0.152542 | 0.162547 | 0.175473 | 0.295436 |
| K-S Rank | | | **1** | **2** | **3** | |
| A-D Test | 33.93114 | 34.36679 | 3.294007 | 4.738318 | 5.883807 | 42.86107 |
| A-D Rank | | | **1** | **2** | **3** | |
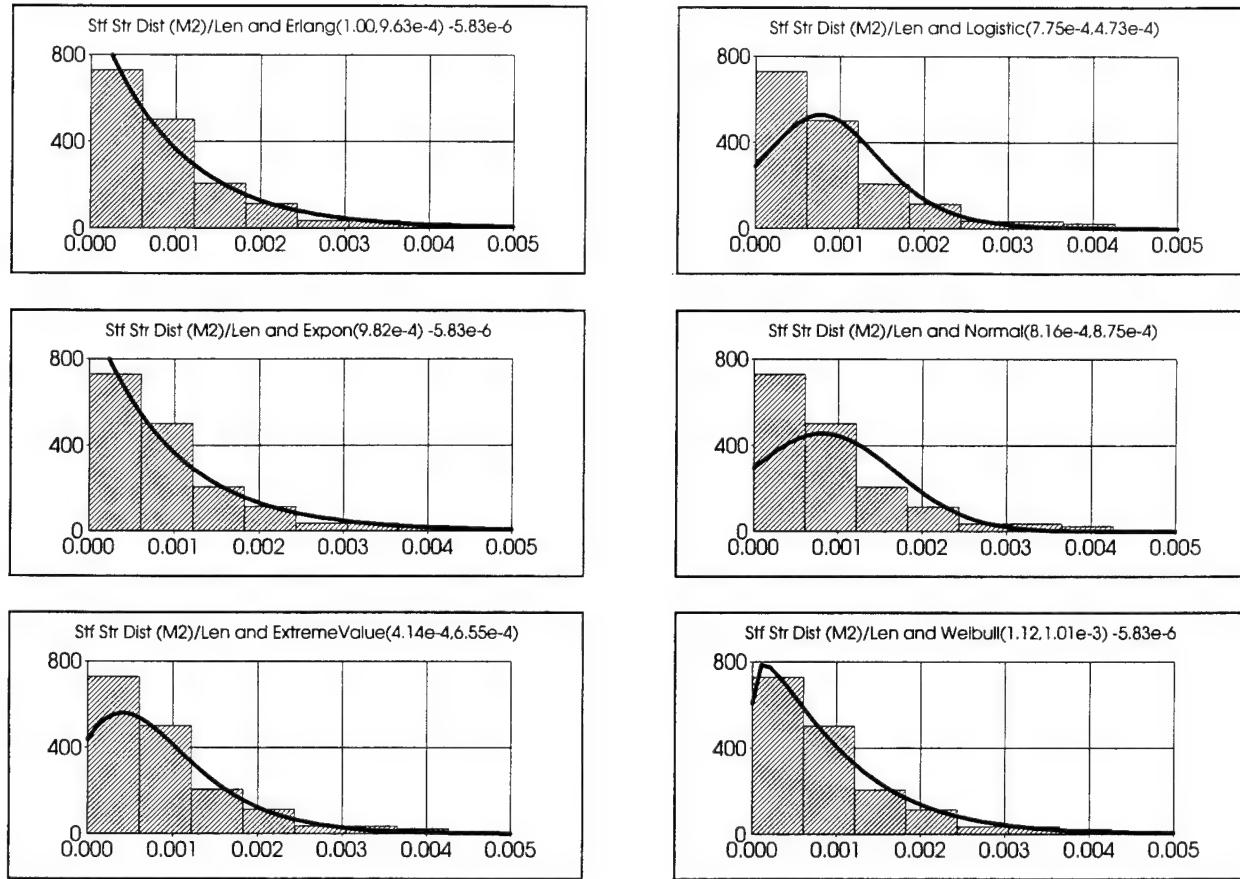
**FIGURE 5.3.3.** Stiffener Strong Axis (Mode II) Distortion Bias (Normalized to Measured Stiffener Length) Distribution Fit with the Most Highly Ranked Probability Density Functions.

# 6.0 FABRICATED OVERALL DIMENSIONS OF SHIPS

## 6.1 Ship Length

The literature review did not reveal any information on uncertainties in the length $L$ of ships, but it can be assumed that the length variability in the form of a standard deviation does not exceed one or two inches with a normal probability distribution. Also, it is assumed that the standard deviation is not a function of length.

## 6.2 Ship Depth

Statistical information on ship depth ($D$) was summarized by Daidola and Basar (1980) as given in Table 6.2a. This table provides statistical information on variation of ship depth based on average tolerance. As in the case of plate thickness $t$, the calculation of standard deviation for ship depth $D$ based on its tolerance can be performed by dividing the tolerance by 3. This calculation leads to correct results, if the underlying probability distribution for $D$ is normal and 99.7 percent of the measurement fall within the tolerance limit. The c.o.v. of $D$ can be simply computed by dividing the standard deviation by the mean of $D$ as shown in Table 6.2a. Daidola and Basar (1980) outlined the necessary steps for the calculation of the c.o.v. of $D$ from measured data. Based on four measured depths, their computed value for the c.o.v. is .001365. Table 6.2b provides averages and ranges for the mean, standard deviation, and c.o.v. of $D$. The calculated averages in Table 6.2b were based on the data shown in Table 6.2a.

**Table 6.2a.** Uncertainty in Ship Depth ($D$) Based on Tolerance.

| Data Point | Tolerance (in) | Standard Deviation of $D$ (ft) | Mean of $D$ (ft) | c.o.v. of $D$ |
|---|---|---|---|---|
| 1 | 1/4 | 0.00694 | 20.0 | 0.000347 |
| 2 | 1/2 | 0.01390 | 36.0 | 0.000386 |
| 3 | 0.1% | 0.01200 | 36.0 | 0.000333 |
| 4 | 1/2 | 0.01390 | 26.0 | 0.000535 |
| 5 | 3/8 | 0.01040 | 91.0 | 0.000114 |
| 6 | 1/2 | 0.01390 | 50.0 | 0.000278 |

**Table 6.2b.** Averages and Ranges for the Statistics of Ship Depth $D$

|  | Mean of $D$ (ft) | Standard Deviation of $D$ (ft) | c.o.v. of $D$ |
|---|---|---|---|
| Average | 43.2 | 0.01180 | 0.0003255 |
| Minimum | 20.0 | 0.00694 | 0.0001140 |
| Maximum | 91.0 | 0.01390 | 0.0005350 |

## 6.3. Ship Breadth

The coefficient of variation of ship breadth ($B$) that is based on fabrication tolerances is given in Table 6.3a (Daidola and Basar 1980). The coefficient of variation was computed to be 0.000181. A value of zero was assumed by Mansour (1972). Table 6.3b provides averages and ranges for the mean, standard deviation, and c.o.v. of $B$.

**Table 6.3a.** Uncertainty in Ship Breadth ($B$) Based on Tolerance.

| Data Point | Tolerance | Standard Deviation of $B$ (ft) | Mean of $B$ (ft) | c.o.v. of $B$ |
|---|---|---|---|---|
| 1 | 0.1% | 0.002 | 6 | 0.0003333 |
| 2 | 1/2 in | 0.0139 | 200 | 0.0000695 |
| 3 | 1/2 in | 0.0139 | 75 | 0.0001853 |
| 4 | 1/2 in | 0.0139 | 96 | 0.0001450 |

**Table 6.3b.** Averages and Ranges for the Statistics of Ship Breadth $B$.

|  | Mean of $B$ (ft) | Standard Deviation of $B$ (ft) | c.o.v. of $B$ |
|---|---|---|---|
| Average | 94.25 | 0.01093 | 0.0001833 |
| Minimum | 6.00 | 0.00200 | 0.0000695 |
| Maximum | 200.00 | 0.01390 | 0.0003333 |

## 6.4. Section Modulus

Table 6.4 provides the ratio of actual ($Z_a$) to minimum (or rules required, $Z_r$) section modulus (i.e., $\frac{Z_a}{Z_r}$ ) for selected ships from different countries and various classification societies (Guedes Soares and Moan 1988). The computed mean value and coefficient of variation for this ratio were found to be 1.04 and 0.05, respectively. Mansour (1993) assumed a lognormal distribution with mean to nominal ratio and coefficient of variation of 1.0 and 0.04, respectively (nominal value was taken to be the section modulus as required by ABS rules).

**Table 6.4.** Ratio of Actual ($Z_a$) to Minimum (Rules Specified, $Z_r$) Section Modulus for Selected Ships

| Ship | $\frac{Z_a}{Z_r}$ | Ship | $\frac{Z_a}{Z_r}$ | Ship | $\frac{Z_a}{Z_r}$ | Ship | $\frac{Z_a}{Z_r}$ |
|---|---|---|---|---|---|---|---|
| CS 3 | 1.04 | OBO 3 | 1.00 | TK7 | 1.00 | TK31 | 1.02 |
| CT 2 | 1.00 | OBO 4 | 1.00 | TK8 | 1.00 | TK32 | 1.02 |
| CT 3 | 1.00 | OBO 5 | 1.06 | TK18 | 1.12 | TK33 | 1.02 |
| BC 5 | 1.00 | OBO 6 | 1.00 | TK19 | 1.12 | TK34 | 1.02 |
| BC 9 | 1.01 | CH 1 | 1.00 | TK20 | 1.12 | TK35 | 1.02 |
| BC 10 | 1.00 | CH 2 | 1.15 | TK21 | 1.12 | TK36 | 1.02 |
| BC 14 | 1.01 | CH 3 | 1.15 | TK22 | 1.00 | TK37 | 1.02 |
| BC 15 | 1.01 | OO2 | 1.02 | TK23 | 1.00 | TK38 | 1.04 |
|  |  | OO3 | 1.02 | TK24 | 1.07 |  |  |

CS = cargo ship, CT = containership, BC = bulk carrier, OBO = ore/bulk/oil carrier, CH = chemical tanker, OO = ore/oil carrier, and TK = oil tanker

# 7.0 CONCLUSIONS

## 7.1 Plate Thickness

The plate thickness data used in this study are drawn from a large range of sources. Extensive analyses may be performed on a data set such as this, with the resulting uncertainty model being of limited use due to its historical nature. The material which is a result of current manufacturing and quality techniques is of interest to the designer, and must be addressed by working with industry. For calibration efforts, the use of the bias and uncertainty as listed in Table 7.1 should suffice. Should the investigator like to consider and include the impact of influences such as material type and source upon the plate thickness uncertainty, they may use the applicable bias and uncertainty values discussed and presented in Section 3.0.

The first p.d.f. is the most appropriate representation of the uncertainty in the plate thickness according to goodness-of-fit methods and visual inspection. For simplified studies, the second p.d.f. may be used. Section 3.0 discusses the analysis of this variable in depth.

**TABLE 7.1.** Plate Thickness Bias, Statistics and Probability Density.

| Bias | Mean | Standard Deviation | c.o.v. (%) | Recommended First p.d.f. | Recommended Second p.d.f. |
|------|------|--------------------|------------|--------------------------|---------------------------|
| Ratio | 1.04849 | 0.04592 | 4.38 | Logistic | Lognormal |
| Difference (in.) | 0.014732 | 0.020997 | n/a | Lognormal | Lognormal |

## 7.2 Stiffener Dimensions

The stiffener dimensions data set has been considered a gross sample, without regard for influences upon the uncertainty such as material type, year of manufacture, type of section (built-up or cold-rolled), etc. The source of this data is from Navy ships, after construction (and years at sea), with a coating of paint, and is primarily from exposed and easily accessible members such as bulkheads. Tables 7.2a and 7.2b present summaries of the information presented and discussed in Section 4.0. The first p.d.f. is the most appropriate representation of the uncertainty

in the variable according to goodness-of-fit methods and visual inspection. For simplified studies, the second p.d.f. may be used.

**TABLE 7.2a.** Stiffener Geometric Property Ratio Bias, Statistics and Probability Density Functions.

| Variable | Mean | Standard Deviation | c.o.v. (%) | Recommended First p.d.f. | Recommended Second p.d.f. |
|---|---|---|---|---|---|
| Length | 0.9882 | 0.04670 | 4.726 | Lognorm | Normal |
| Spacing | 0.9922 | 0.02816 | 2.838 | Logistic | Normal |
| Depth | 0.9955 | 0.01859 | 4.726 | Logistic | Normal |
| Web Thick. | 1.2550 | 0.11339 | 9.035 | LogLogistic | Lognormal |
| Flange Breadth | 1.0144 | 0.01634 | 1.611 | Logistic | Lognormal |
| Flange Thick. | 1.1321 | 0.10377 | 9.167 | Extreme Value Type I | Lognormal |

**TABLE 7.2b.** Stiffener Geometric Property Difference Bias, Statistics and Probability Density Functions.

| Variable | Mean (in.) | Standard Deviation (in.) | Recommended First p.d.f. | Recommended Second p.d.f. |
|---|---|---|---|---|
| Length | -1.2640 | 4.8189 | Logistic | Normal |
| Spacing | -0.2514 | 0.8669 | Logistic | Normal |
| Depth | -0.0281 | 0.1171 | Logistic | Normal |
| Web Thick. | 0.0503 | 0.0180 | Weibull | Normal |
| Flange Breadth | 0.0587 | 0.0649 | Logistic | Normal |
| Flange Thick. | 0.0293 | 0.0212 | Extreme Value Type I | Lognormal |

## 7.3 Distortions

Table 7.3 shows a summary of the basic statistics associated with each type of distortion. The first p.d.f. is the most appropriate representation of the uncertainty in the distortion variable according to goodness-of-fit methods and visual inspection. For simplified studies, the second p.d.f. may be used. Section 5.0 discusses the analysis of these distortion variables in depth.

**TABLE 7.3.** Stiffener Geometric Property Ratio Bias, Statistics and Probability Density Functions.

| Variable | Normalized by | Mean | Standard Deviation | Recommended First p.d.f. | Recommended Second p.d.f. |
|---|---|---|---|---|---|
| Unstiffened Panel Distortion | Panel Breadth | 0.010821 | 0.010634 | LogLogistic | Exponential |
| Unstiffened Panel Distortion | Plate Thickness | 0.786791 | 0.921504 | Weibull | Exponential |
| Weak Axis Stiffener Distortion | Stiffener Length | 8.0653E-04 | 8.1621E-04 | LogLogistic | Exponential |
| Strong Axis Stiffener Distortion (Mode I) | Stiffener Length | 3.6453E-04 | 4.3743E-04 | Extreme Value Type I | Exponential |
| Strong Axis Stiffener Distortion (Mode II) | Stiffener Length | 8.1615E-04 | 8.7497E-04 | Extreme Value Type I | Exponential |

## 7.4 Overall Dimensions

The uncertainty associated with the larger ship dimensions is discussed in Section 6.0, and is the result of a literature review. The use of these values is appropriate in lieu of more information or study.

## 7.5 Recommendations

The efficient use of reliability methodology requires control of the process which is being (re-)engineered. Uncertainty in the strength basic variables should not be considered a fixed quantity. A survey of the uncertainties in the past designs (as are discussed in this report) are not necessarily the same as the uncertainties in present and future designs. Changes to manufacturing processes upon which the basic strength variables are dependent must be considered as a primary cause of changes to this uncertainty, with the resulting uncertainty measured and incorporated into the designers tools. To accurately include the uncertainty of the basic variables in the prediction of ship structural strength, their variability must be controlled in a manner which allows input into the design process. Communication between the designer, supplier, and shipyard must be incorporated into the design and construction process.

As the designers resources do not allow complete control of the all the basic strength variables, effective management of the strength uncertainty will require identification of the basic strength variables which exert the most influence upon the strength prediction. This may be achieved through the utilization of the results of this report in an assessment of the strength or reliability model sensitivity to these variables. A source of potential methods are discussed in Hess et al (1994), Hughes et al (1994), Mansour and Wirsching (1995), and Nikolaidis and Kaplan (1991). Ranking of the basic variables by importance will allow control to be applied to those variables which are most influential on the strength uncertainty.

The statistical models (probability density functions) chosen to represent the uncertainty found in the basic strength variables may have great impact upon the strength and reliability predictions. To better understand the dependency of the strength and reliability models on the chosen p.d.f.'s, a sensitivity study should be conducted. A study of this nature would allow the investigator to determine whether or not the choice of a p.d.f. is appropriate.

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# APPENDIX A:  PROBABILITY DENSITY FUNCTIONS

The statistical distributions used to model the variability in the geometry and imperfections of surface ship structures are discussed below.  Only the probability density functions (p.d.f.'s) are presented, for other forms and a more comprehensive treatment of distributions see Ayyub and Chao (1994), *BestFit User's Guide* (1995),  and Evans et al (1993).  The p.d.f.'s and their associated parameters presented in the main text are discussed and converted to nomenclature as presented in Ayyub and Chao (1994).  The p.d.f. of variable $x$ is $f_X(x)$.  The *adjustments* discussed in the main report (additions, subtractions, multiplication's and/or divisions) are modifications applied to the $f_X(x)$ described below.

## Beta Probability Density Function

Density:

$$f_X(x) = \frac{x^{(q-1)}(1-x)^{(r-1)}}{B[q,r]}$$

$$B[q,r] = \int_0^1 t^{(q-1)}(1-t)^{(r-1)} dt$$

Parameters:
  Parameter 1 = $q$,  where $q > 0$.
  Parameter 2 = $r$,  where $r > 0$.
Domain:
  $0 \leq x \leq 1$.

## Chi-Square Probability Density Function

Density:

$$f_X(x) = \frac{x^{(\frac{v}{2}-1)} e^{\frac{-x}{2}}}{2^{\frac{v}{2}} \Gamma\left[\frac{v}{2}\right]}$$

$\Gamma[\varphi]$ is the Gamma Function.

Parameters:
  Parameter 1 = $v$,  where $v > 0$ and is an integer.
Domain:
  $x \geq 0$.

## Erlang Probability Density Function

Density:

$$f_X(x) = \frac{\beta^{(-m)} x^{(m-1)} e^{\frac{-x}{\beta}}}{\Gamma[m]}$$

$\Gamma[\varphi]$ is the Gamma Function.

Parameters:

Parameter $1 = m$, where $m > 0$ and is an integer.

Parameter $2 = \beta$, where $\beta > 0$.

Domain:

$x \geq 0$.

## Exponential Probability Density Function

Density:

$$f_X(x) = \lambda e^{(-\lambda x)}$$

Parameters:

Parameter $1 = 1/\lambda$, where $\lambda > 0$. (Parameter 1 in the main text is the inverse of the normally used parameter $\lambda$.)

Domain:

$x \geq 0$.

## Extreme Value Type I (Gumbel) Probability Density Function

Note: Ayyub and Chao (1994) consider this as Type I Largest.

Density:

$$f_X(x) = \alpha \exp[-\alpha(x-u)] \exp\{-\exp[-\alpha(x-u)]\}$$

Parameters:

Parameter $1 = u$.

Parameter $2 = 1/\alpha$, where $\alpha > 0$.

Domain:

$-\infty \leq x \leq \infty$.

## Gamma Probability Density Function

Density:

$$f_X(x) = \frac{\beta^{(-\alpha)} x^{(\alpha-1)} e^{\frac{-x}{\beta}}}{\Gamma[\alpha]}$$

$\Gamma[\varphi]$ is the Gamma Function.

Parameters:

Parameter 1 = $\alpha$, where $\alpha > 0$.

Parameter 2 = $\beta$, where $\beta > 0$.

Domain:

$x \geq 0$.

## Inverse Gaussian (Wald) Probability Density Function

Density:

$$f_X(x) = \left(\frac{\lambda}{2\pi x^3}\right)^{\frac{1}{2}} \exp\left[\frac{-\lambda(x-\mu)^2}{2\mu^2 x}\right]$$

Parameters:

Parameter 1 = $\mu$, where $\mu > 0$.

Parameter 2 = $\lambda$, where $\lambda > 0$.

Domain:

$x > 0$.

## Logistic Probability Density Function

Density:

$$f_X(x) = \frac{\exp\left[-(x-\alpha)/\beta\right]}{\beta\left\{1 + \exp\left[-(x-\alpha)/\beta\right]^2\right\}}$$

Parameters:

Parameter 1 = $\alpha$.

Parameter 2 = $\beta$, where $\beta > 0$.

Domain:

$-\infty \leq x \leq \infty$.

## Log Logistic Probability Density Function

Density:

$$f_X(x) = \frac{\alpha\left(\dfrac{x-\gamma}{\beta}\right)^{\alpha-1}}{\beta\left[1+\left(\dfrac{x-\gamma}{\beta}\right)^{-\alpha}\right]^2}$$

Parameters:

   Parameter 1 = $\gamma$.
   Parameter 2 = $\beta$, where $\beta > 0$.
   Parameter 3 = $\alpha$, where $\alpha > 0$.

Domain:

   $x > \gamma$

## Lognormal Probability Density Function

Density:

$$f_X(x) = \frac{1}{x\sqrt{2\pi\sigma_Y^2}}\exp\left[\frac{-\{\ln(x)-\mu_Y\}^2}{2\sigma_Y^2}\right]$$

$$\mu_Y = \ln\left[\frac{\mu^2}{\sqrt{\sigma^2+\mu^2}}\right] \text{ and } \sigma_Y = \sqrt{\ln\left[\frac{\sigma^2+\mu^2}{\mu^2}\right]}$$

Parameters:

   Parameter 1 = $\mu$, where $\mu > 0$.
   Parameter 2 = $\sigma$, where $\sigma > 0$.

Domain:

   $x > 0$

## Normal (Gaussian) Probability Density Function

Density:

$$f_X(x) = \frac{1}{x\sqrt{2\pi\sigma^2}}\exp\left[\frac{-\{x-\mu\}^2}{2\sigma^2}\right]$$

Parameters:

   Parameter 1 = $\mu$.
   Parameter 2 = $\sigma$, where $\sigma > 0$.

Domain:

   $-\infty \le x \le \infty$.

## Pearson Type 5 Probability Density Function

Density:

$$f_X(x) = \frac{x^{-(\alpha+1)}\exp\left[-\dfrac{\beta}{x}\right]}{\beta^{-\alpha}\Gamma[\alpha]}$$

$\Gamma[\varphi]$ is the Gamma Function.

Parameters:

Parameter 1 = $\alpha$, where $\alpha > 0$.

Parameter 2 = $\beta$, where $\beta > 0$.

Domain:

$x > 0$.

## Pearson Type 6 Probability Density Function

Density:

$$f_X(x) = \frac{\left(\dfrac{x}{\beta}\right)^{\alpha_1-1}}{\beta B[\alpha_1,\alpha_2]\left(1+\dfrac{x}{\beta}\right)^{\alpha_1-\alpha_2}}$$

$$B[\alpha_1,\alpha_2] = \int_0^1 t^{\alpha_1-1}(1-t)^{\alpha_2-1}\,dt$$

Parameters:

Parameter 1 = $\alpha_1$, where $\alpha_1 > 0$.

Parameter 2 = $\alpha_2$, where $\alpha_2 > 0$.

Parameter 3 = $\beta$, where $\beta > 0$.

Domain:

$x \geq 0$.

## Rayleigh Probability Density Function

Density:

$$f_X(x) = \frac{x}{\alpha^2}\exp\left[-\frac{x^2}{2\alpha^2}\right]$$

Parameters:

Parameter 1 = $\alpha$, where $\alpha > 0$.

Domain:

$x > 0$.

## Triangular Probability Density Function

Density:

$$f_X(x) = \frac{2(x-a)}{(b-a)(c-a)} \qquad \text{if } a \leq x \leq b.$$

$$f_X(x) = \frac{2(c-x)}{(c-a)(c-b)} \qquad \text{if } b < x \leq c.$$

Parameters:

Parameter 1 = $a$, where $a$ is the minimum.
Parameter 2 = $b$, where $b$ is the most likely.
Parameter 3 = $c$, where $c$ is the maximum.
$$a \leq b \leq c$$

Domain:

$$a \leq x \leq c.$$

## Uniform Probability Density Function

Density:

$$f_X(x) = \frac{1}{b-a}$$

Parameters:

Parameter 1 = $a$, where $a$ is the minimum.
Parameter 2 = $b$, where $b$ is the maximum.
$$a \leq b$$

Domain:

$$a \leq x \leq b.$$

## Weibull Probability Density Function

Density:

$$f_X(x) = \beta \alpha^{-\beta} x^{\beta-1} \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right]$$

Parameters:

Parameter 1 = $\beta$, where $\beta > 0$.
Parameter 2 = $\alpha$, where $\alpha > 0$.

Domain:

$$x > 0.$$

# APPENDIX B:  GOODNESS-OF-FIT TESTS

Goodness-of-fit tests provide the investigator with a measure of the degree to which the sample data belongs to a hypothesized theoretical distribution.  The goodness-of-fit statistic is a metric which allows a relative comparison between the fits of different p.d.f.'s for each test.  Further discussion of the implementation of these tests may be found in Allen (1990), Ang and Tang (1975), Ayyub and McCuen (1997), *BestFit User's Guide* (1995), Modarres (1993), and Sheaffer and McClave (1982).

## Chi-Squared Goodness-of-Fit Test

The chi-squared test is the most commonly used goodness-of-fit test, and the most commonly discussed test found in statistics texts.  It may be applied to both continuous and discrete probability density functions.  It is also the easiest to implement, requiring the least amount of computational power (Allen, 1990).  A weakness is that the resulting measure of the goodness-of-fit of a p.d.f. to the input data is highly dependent upon the interval selection.  This allows different conclusions to be drawn from the same data set. (*BestFit User's Guide*, 1995).

## Kolmogorov-Smirnov Goodness-of-Fit Test

The Kolmogorov-Smirnov test does not depend on the number of intervals making it more powerful than the chi-squared test.  It cannot be used for discrete distributions and also does not work well in judging the fit of the tails of the distribution (*BestFit User's Guide*, 1995).

## Anderson-Darling Goodness-of-Fit Test

The Anderson-Darling test  is similar to the Kolmogorov-Smirnov test, with more attention paid to the tails of the distribution.  It also is not dependent upon the selection of interval sizes (*BestFit User's Guide*, 1995).

# APPENDIX C:  STRUCTURAL MEMBER SURVEY (NSWCCD 625)

## Background:

NSWCCD 625 is providing support for the structural member survey during TDY visits to US Navy ships for other tasks.  The ship is normally scouted for likely sample candidates where there is ease of access (such as few interference's and no thermal or acoustic insulation).

## Scope:

Working with forms developed in FY93, the following dimensional information is obtained: stiffener depth; flange width; web thickness; plate thickness; stiffener length and stiffener spacing.  Subsequent to that, distortion information is taken including:  plate distortion; stiffener weak axis and strong axis distortions.

## Methods:

Structural member survey is started by drawing a rough sketch of the area to be surveyed identifying stiffeners by number, plate areas by letter, deck level, frame and compartment number.

*Stiffener Measurements*

- Stiffener depth is measured at the edge of the flange on both sides at three places along its length; the extreme ends and at the middle of the span.  The measurements are taken perpendicular to the face of the flange.

- The flange width dimension is taken at three places along the length of the stiffener; also at the extreme ends and at the middle of the span.

- Stiffener length shown on the form is the length of the web to its welded connection unless there is a significant discontinuity in the stiffener.  In that case, the length shown is to the weld connection at the discontinuity.  The sketch should indicate any discontinuities.

- Stiffener spacing is also measured at the extreme ends and at mid-span. This dimension is taken flange-edge to flange-edge to provide a centerline-to-centerline dimension of the spacing.

- Thicknesses are taken two ways depending on equipment availability. When available, a UT thickness meter is used to find flange and web thicknesses. The readings are again taken at extreme ends and mid-span along the length. The web dimension is at mid-depth and the flange dimension at the middle of one leg or another of the flange.**

- In the absence of the UT meter, micrometers are used for these measurements. For the web, then, readings are only taken where snipes have been cut or the flange is not continuous at one end.

- Plate thickness of the bulkhead or deck can only be determined when using the UT meter. This reading is taken at the approximate center of the plate.**

*Distortion Measurements*

- Plate distortion is measured by establishing a three-by-three grid over the plate. String is attached to stiffeners on either side of the plate. Measurements are then taken from the string to the plate at three places (at the ends and at mid-span). This procedure is repeated two more times to complete the matrix. When adjacent beams are vertical, the string is placed at the top, mid-span and the bottom. When the adjacent beams are horizontal, the string is placed forward, mid-span and aft or outboard, mid-span and inboard.

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** It should be noted that all the thickness measurements include paint coating. (ie. paint was not removed for any of the measurements)

- Stiffener weak axis distortion is determined by clamping a string along the edge of the flange. It is configured so that it is parallel to but not touching the flange face. Again, the offsets are measured at extreme ends and at mid-span.

## Accuracy

The data forms indicate the level of accuracy for each dimension. The degree of error is:

a) for dimensions measured in fraction of an inch, the degree of error is one half the level of accuracy.

b) for dimensions measured in mils, the degree of error is one tenth the level of accuracy.